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**DESENVOLVIMENTO DE UM MÉTODO DE DETEÇÃO
DE CNVs ATRAVÉS DE qPCR**

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**Desenvolvimento de um método de deteção de
CNVs através de qPCR**

*Development of a CNVs detection method through
qPCR*

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Biotecnologia, realizada sob a orientação científica da Doutora Gabriela Maria Ferreira Ribeira de Moura, Professora Auxiliar do Departamento de Ciências Médicas da Universidade de Aveiro e coorientação da Dra. Maria de Fátima e Costa Torres, Especialista em Genética Humana, Coordenadora de área do Laboratório de Diagnóstico Molecular do CGC Genetics.

Para os meus pais. Por me terem dado a vida, dou-vos agora o melhor de mim.

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Palavras-chave

Array Comparative Genomic Hybridization (aCGH); Copy Number Variations (CNVs); Deep Sequencing; Diagnóstico Molecular; Fluorescent in situ Hybridization (FISH); Multiplex Ligation-Dependent Probe Amplification (MLPA); PCR quantitativo em tempo real (qPCR); Single Nucleotide Polymorphism Arrays; SYBR-Green I; Validação

Resumo

Os *copy number variations* (CNVs) consistem em segmentos de DNA de uma kilobase ou mais, que se encontram num número variável de cópias, em comparação com um genoma de referência. A detecção de CNVs é convencionalmente realizada através de técnicas de citogenética, como *fluorescence in situ hybridization* e *array comparative genomic hybridization*, ou com base em PCR, como *multiplex ligation-dependent probe amplification*, *SNP arrays* ou *deep sequencing*. Porém, a evolução da técnica de PCR quantitativo em tempo real (qPCR) permitiu que fosse, actualmente, considerada o método *gold standard* para a detecção de CNVs devido, sobretudo, ao elevado rendimento, sensibilidade, precisão e versatilidade. O presente trabalho descreve o desenvolvimento e validação de um método de detecção de CNVs através da técnica de qPCR. A metodologia adotada provou ser um método preciso e sensível para a detecção de CNVs em regiões específicas.

Keywords

Array Comparative Genomic Hybridization (aCGH); Copy Number Variations (CNVs); Deep Sequencing; Molecular Diagnosis; Fluorescent *in situ* Hybridization (FISH); Multiplex Ligation-Dependent Probe Amplification (MLPA); real time quantitative PCR (qPCR); Single Nucleotide Polymorphism Arrays; SYBR-Green I; Validation

Abstract

Copy number variations (CNVs) consist in DNA segments of one kilobase or larger, that are present in variable copy number, in comparison to a reference genome. CNVs detection is conventionally performed through cytogenetic, such as fluorescence *in situ* hybridization and array comparative genomic hybridization, or PCR-based techniques, like multiplex ligation-dependent probe amplification, SNP arrays or deep sequencing. However, the evolution of quantitative PCR (qPCR) allows it to be considered the gold standard for CNVs detection, mainly due to its high throughput, precision and versatility. The present work describes the development and validation of a qPCR method for CNVs detection. This method proved to be an accurate and sensitive method for CNVs detection in targeted regions.

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Abbreviations

$2^{-\Delta\Delta C_t}$ method – Delta Delta Ct method
aCGH – array comparative genomic hybridization
BAC - bacterial artificial chromosomes
BCKD – branched-chain alpha-keto acid dehydrogenase
BM – Bethlem myopathy
bp – base pair
CGH – comparative genomic hybridization
CNVs – Copy Number Variations
Cq – quantification cycle
Ct – threshold cycle
dbGaP – Database of Genotype and Phenotype
DGV – Database of Genomic Variants
DGV – Database of Genomic Variants
DNA – deoxyribonucleic acid
dsDNA – double stranded DNA
EDTA – Ethylenediamine tetraacetic acid
FISH – fluorescence *in situ* hybridization
FRET – fluorescence resonance energy transfer
GWAS – genome-wide association studies
HGMD – Human Gene Mutation Database
HGMD – The Human Gene Mutation Database
ISCA – International Standards for Cytogenomic Array
kb – kilobase

LMS – Lenz microphthalmia syndrome
LPO – left probe oligonucleotide
Mb – megabase
MLPA – multiplex ligation-dependent probe amplification
MSUD – Maple Syrup Urine Disease
NCBI - National Center for Biotechnology Information
NGS – Next-generation sequencing
NM – Nucleotide NCBI Reference Sequence
NTC – No-template control
PCR – polymerase chain reaction
qPCR – real-time quantitative polymerase chain reaction
RPO – right probe oligonucleotide
SNP – single nucleotide polymorphism
Ta – annealing temperature
Tm – melting temperature
UCMD – Ullrich congenital muscular dystrophy
VOUS – variants of unknown significance
XLA – X-linked agammaglobulinemia

Introduction

Copy Number Variations

Copy number variations (CNVs) are defined by Feuk and colleagues as DNA segments of one kilobase (1kb) or larger that are present at a variable copy number, in comparison to a reference genome¹. CNVs can be simple in structure, such as gains (tandem duplications or insertional transpositions) and losses (deletions), or may involve complex rearrangements of the genome, such as gains or losses of homologous sequences at multiple sites in the genome^{2,3}. Over the years, new variations in the repetitive regions of DNA have been identified, suggesting that CNVs might be as important to genomic diversity as single nucleotide polymorphisms (SNPs)^{4,5}. In fact, CNVs might account for about 1% of the inter-individual variation, over the 0,1% accounted for SNPs⁶.

The HapMap Project revealed that regions with copy number variation cover approximately 12% of the human genome, and other studies found out that approximately one-third of them are unique to the human species. Regarding evolution, through multiple generations, deletions are usually selected against, while duplications may experience positive selection, as suggested by the existence of gene families⁴. Large CNVs usually exist due to *de novo* events, since they typically suffer negative selection⁵. CNVs <1kb in size are of particular importance to genetic medicine, since they are more numerous than the larger CNVs⁷. Also, CNVs generally are located outside of coding sequences and ultra-conserved regulatory elements, which are sequences of at least 200bp that are 100% conserved across several species². CNVs can involve one or multiple genes, being presented as a recessive or dominant allele, due to variations in gene expression through gene dosage effects. Also, gene expression can be altered through position effects due to the disruption of the coding region or deletions or duplications outside the coding sequences^{2,7}.

Regarding functional categories, genes involved in cell adhesion, the sensory perception of smell, neurophysiological processes, brain development, and responses to chemical stimuli, such as immune responses and drug metabolism, are the most enriched in CNVs^{4,7}. On the other hand, genes involved in cell signalling and cell proliferation, as well as in regulation of protein phosphorylation are the less represented⁴. While some CNVs have no apparent influence on phenotype, others have been implicated in the aetiology of

monogenetic and complex disorders^{4,7}. Also, their interaction with additional genetic or environmental factors may influence detection of their phenotypic effect⁴.

Routine screening in clinical diagnostics passes by the measurement and analysis of CNVs, which can assist in subsequent prognostic monitoring. The currently used techniques applied in CNV studies are fluorescence *in situ* hybridization (FISH), comparative genome hybridisation (CGH), single nucleotide polymorphism (SNP) arrays, deep sequencing, multiplex ligation-dependent probe amplification (MLPA), and real-time quantitative PCR (qPCR)^{8,9}.

Fluorescence *in situ* Hybridization

Fluorescence *in situ* Hybridization (FISH), is a molecular cytogenetic technique that allows direct examination of chromosomal DNA molecules and the visualization of specific sequences in the nucleus and/or on metaphase chromosomes^{7,10}. FISH uses fluorescently labelled DNA probes that are hybridized to metaphase chromosome spreads or interphase nuclei, immobilized on a glass slide^{7,10}. Thus, it allows to locate the physical position of specific DNA sequences that hybridize to the probes on the chromosomes, through examining of the preparation with a microscope^{10,11}.

There are several FISH-based techniques that can be performed, depending on the application. The visualization and analysis of genetic changes affecting one or a few specific genes or loci in individual interphase nuclei can be performed through FISH¹². Fiber-FISH has the highest resolution, ranging from 5 to 500kb, being the preferred method to precisely determine the genomic structure of complex CNVs⁷. Also, FISH can be performed with multiple labelled probes with different fluorochromes, being widely used in clinical diagnosis in order to confirm the presence of CNVs, for example^{7,10}.

However, FISH has several limitations. FISH analysis requires the availability of the specific probe for the gene or locus of interest, with the appropriate size and location and so, it cannot be used to screen unknown genetic aberrations¹². Additionally, locus-specific probes are expensive and the procedure is time-consuming and labour intensive⁷. Also, smaller copy number changes (less than 10kb) are too small to be detected by FISH, requiring other molecular methods¹². Moreover, only a limited number of chromosomal loci can be screened in a single experiment⁷.

Comparative Genomic Hybridization and Array Comparative Genomic Hybridization

Comparative genomic hybridization is a cytogenetic molecular technique, introduced around the 1990s, that allows genome-wide screening for CNVs^{6,13}. It provides alternative means for cytogenetic analysis such as banding patterns (G-banded karyotyping) and FISH. In CGH, a test and a control genome are differentially labelled and competitively hybridized to metaphase chromosomes. The fluorescent signal intensity of the labelled test DNA relative to that of the reference DNA can be linearly plotted across each chromosome, allowing for the identification of copy number changes. CGH can be used to quickly scan an entire genome for imbalances, and does not require cells that are undergoing division. However, the resolution of the CGH has been limited to alterations of approximately 5-10Mb for most clinical applications¹⁴.

Array CGH (aCGH) combines the principles of CGH with the use of microarrays, in order to overcome some limitations of conventional CGH. It uses slides arrayed with small segments of DNA as the targets for analysis, instead of metaphasic chromosomes, allowing to test a smaller sample size^{14,15}. These microarrays are created by the immobilization of small amounts of DNA (probes) on a solid support, in an ordered manner¹⁴. Probes vary in size, from large genomic clones, such as the earlier bacterial artificial chromosomes (BAC), to synthesized oligonucleotides⁶. The BAC-based arrays allow the detection of single-copy losses or gains, usually being targeted to subtelomeric and pericentromeric regions and areas within the genome known to be associated with diseases, such as microdeletion and microduplication syndromes^{6,16,17}. The more frequently used though are oligonucleotide aCGH, which allows genome-wide interrogation and more precise identification of breakpoints, providing high accuracy and reproducibility^{6,18}. The oligonucleotides represent areas of interest, being more flexible in terms of probe selection and facilitating high probe density and customization of array content^{14,16}. Arrays designed specifically for copy number analysis use longer oligonucleotide probes (~60-mer), that provide a better signal-to-noise ratio than the shorter oligonucleotide probes (~22-mer) used in some SNP-detecting array platforms¹⁷. The resolution of aCGH (up to 1kb) is

higher than that of conventional CGH and is determined by considering both probe size and the genomic distance between DNA probes (probe density)^{14,15}.

The basic methodology for aCGH analysis is independent of the probe type¹⁴. The experimental design will depend on the objective of the study, as well as on the sources of variability¹⁹. Most studies apply the reference design (Figure 1), where initially, DNA is extracted from a test sample, followed by the labelling with a fluorescent dye of a specific colour^{14,19}. On the other hand, DNA extracted from a normal control sample, usually from several healthy donors, is labelled with a dye of a different colour^{14,18}. Both DNAs are then mixed together in equal proportions and applied to a microarray¹⁵. The single-stranded denatured DNA from both the sample and control competes to hybridize with the array single-stranded probes, and any unbound DNA is stringently removed by washing^{14,18}. However, this design uses half of the available resources to analyse a reference sample that is not of biological interest, not being cost effective. Alternatively, the dye-swap design, that also needs an on-chip reference sample, reduces artifacts due to the probe-specific dye biases. In the dye-swap design, each sample is run in duplicate, with one of the replicates labelled with the Cy3 dye and the other on a separate array with the Cy5 dye. Nevertheless, this requires the

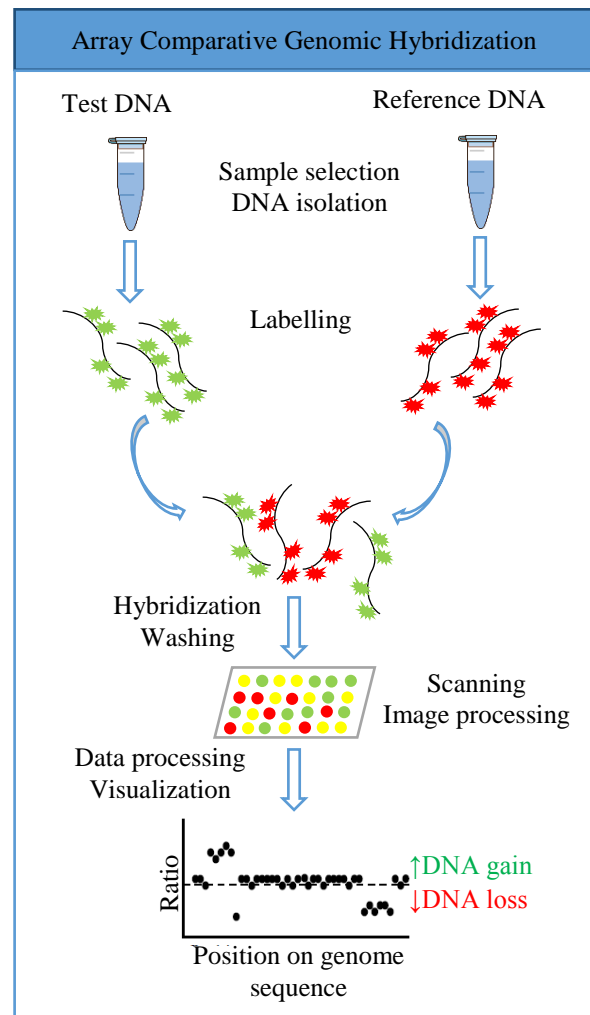


Figure 1 – Overview of the reference design for array comparative genomic hybridization.

The extracted test and reference DNA are labelled with different fluorescent dyes and mixed together in equal proportions. Then, they are applied to a microarray and both DNAs compete to hybridize with the array probes. The relative fluorescence intensities are captured and quantified by digital systems and the fluorescence ratio between the two signals is determined at different positions along the genome. Adapted from Szuhai, K. & Vermeer, M. *Microarray Techniques to Analyze Copy-Number Alterations in Genomic DNA: Array Comparative Genomic Hybridization and Single-Nucleotide Polymorphism Array*. *J. Invest. Dermatol.* 135, 1–5 (2015).

doubling of every sample hybridization, increasing the cost of the study in comparison to the reference design. Another set of design does not require on-chip reference samples, since off-chip references can be utilized. The use of an off-chip reference processed on the same day possesses similar precision in copy-number estimates as an on-chip reference. In a balanced-block design, two groups of interest can appear on each assay simultaneously. If there are more than two groups of interest, not every group can appear at the same time on each array, resulting in a balanced incomplete-block design. Although balanced-block and incomplete-block designs still require that each group is half labelled with Cy3 fluorescent dye and the other half labelled with Cy5 fluorescent dye, they are more efficient than a reference design. Also, these designs allow investigators to nearly double their sample size while using the same number of arrays as required for a reference design. This increases the statistical power, which is very important in genome-wide research studies exploring the association between copy number and disease¹⁹. Regardless of the previously chosen design, the relative fluorescence intensities of the labelled DNA probes that have hybridized to each target are captured and quantified by digital imaging systems. The fluorescence ratio of the test and reference hybridization signals is determined at different positions along the genome. This provides information on the relative copy number of sequences in the test genome as compared to the normal genome^{14,15}.

The main advantage of aCGH is its capacity to simultaneously detect aneuploidies, deletions, duplications, and/or amplifications of any locus represented on an array, also being less labour-intense and expense-saving, with a faster turnaround time^{14,15}. The application of aCGH on the high resolution measurement of gains and losses of DNA sequence was developed by Pinkel and colleagues^{7,20}. Since then, multiple whole genome CNVs studies in normal populations have emerged, now being a commonly ordered clinical genetic test^{16,17}. It is a powerful tool for the detection of sub-microscopic chromosomal abnormalities in individuals with idiopathic intellectual disability and various birth defects¹⁴. The sensitivity of aCGH is determined by the number and density of the probes and their resolution, and it must accurately detect imbalances smaller than 5Mb in order to be advantageous over G-band karyotyping¹⁶. Also, an international consensus statement recommended aCGH as a first-line genetic test, instead of conventional karyotype analysis, for patient with unexplained developmental delay/intellectual disability, autism spectrum disorders, and multiple congenital

anomalies^{17,21}. The use of oligo arrays have improved aCGH resolution, which allows better detection and mapping of localized changes, such as microdeletions and microduplications^{16,22}. Moreover, aCGH testing can be subjected to automation, high-throughput objective analysis and quality control^{15,16}.

However, aCGH can only potentially detect “unbalanced chromosomal changes”, failing to detect balanced genomic rearrangements, such as translocations or inversions, since the amount of DNA within the sample does not differ from the control DNA, as well as low-level mosaicism^{15–17}. Also, polyploidies are not detected because there is no loss or gain of DNA content at a scale smaller than the chromosome¹⁵. In addition, the identification of novel variants of unknown significance (VOUS) through aCGH may cause difficulties in clinical management, since they cannot be clearly classified as benign or pathogenic^{15,16}. Therefore, the development of CNVs databases, such as the International Standards for Cytogenomic Array (ISCA) Consortium from within the Database of Genotype and Phenotype (dbGaP) at the National Center for Biotechnology Information and the Database of Genomic Variants (DGV) facilitates the resolution of VOUS into benign or pathogenic variants^{16,17}. The key to overcome this disadvantage is to increase sensitivity and specificity, through the selection of a microarray that is capable of detecting the majority of pathological CNVs without detecting too many VOUS¹⁶. Up to date, aCGH is more expensive than conventional cytogenetic testing, since higher probe density increases the cost per analysed sample^{15,18}.

Single Nucleotide Polymorphism Arrays

Single Nucleotide Polymorphism (SNP) Arrays are widely used for genome-wide association studies (GWAS), which contributed greatly for population genetics and genetic epidemiology²³. Nevertheless, the widespread availability of SNP array data contributed to its application in CNV discovery and mapping^{7,23}. Nowadays, commercial SNP arrays offer high genomic coverage, at somewhat affordable prices and improvements in genomic regions previously problematic²³.

SNP arrays are based on hybridizations with SNP marker probes designed specifically for particular genomic locations, typically targeting biallelic SNPs. For each SNP, an array platform includes two types of hybridization probes specific to two types of

known alleles. Thus, the SNP genotype can be determined by the ratios of the hybridization intensities for each probe, which can be altered due to CNVs. Computational methods use hybridization intensities and allele frequencies from SNP markers, in order to detect common or rare CNVs²⁴.

The main limitations of SNP arrays are that they are still relatively expensive and not ideal when thousands of samples need to be screened. Moreover, the power of SNP arrays is limited by their resolution by a lower detection limit of ~10–25 kb⁷.

Deep Sequencing

Next-generation sequencing technologies (NGS) are based on various implementations of cyclic-array sequencing, redefining the study of CNVs. NGS platforms allow for the sequencing of millions of short DNA fragments simultaneously and may process a whole human genome in a relatively short period of time and at a reasonable price²⁵.

Nowadays, rapidly developing NGS technologies provide a sensitive and accurate alternative approach for accessing genomic variations²⁶. Short reads from NGS platforms are randomly sampled from the entire genome, as opposed to array-based approaches, where probes are predefined for limited genomic regions. The NGS approach also has the advantages of possessing a higher coverage and resolution, more accurate estimation of copy numbers, more precise detection of breakpoints, and higher capability to identify novel CNVs²⁷. However, the use of NGS for CNV identification has been limited by a lack of available and effective statistical approaches²⁶.

Multiplex Ligation-dependent Probe Amplification

Multiplex ligation-dependent probe amplification (MLPA) was first described in 2002 by Schouten and colleagues and developed for the detection of large mutations in disease-related genes^{28,29}. It is a PCR-based technique that has been applied to the investigation of a wide variety of genetic disorders, expression analysis, methylation identification, multi-colour labelling as well as stuffer-free and multiple-oligo probe design^{29,30}. MLPA is used for the large-scale screening of samples for the presence of copy

number variations at the genomic level (gains or losses) in a test DNA, compared to a control^{31,32}. Several studies have demonstrated that MLPA allows sensitive and accurate detection of disease-specific clinically significant copy number changes³⁰. Furthermore, two variations of MLPA have been developed for mRNA profiling (RT-MLPA) and methylation profiling (MS-MLPA)³³.

In MLPA, probe pairs are designed against genomic regions of interest (test probes), along with another set of probes that serve as reference probes, being able to utilize up to 45 specific probes for different DNA sequences^{32,34}. Each MLPA probe (Figure 2) consists of two oligonucleotide half-probes, with target-specific sequences, that anneal to adjacent sites on DNA, and a generic primer pair attached to the upstream half-probe (also known as short probe and/or left probe oligonucleotide, LPO) at its 5' end and to the downstream half-probe (also known as right probe oligonucleotide, RPO) at its 3' end³²⁻³⁴. Moreover, one or both half-probes contain a stuffer sequence, which allows the differentiation of the reference and test probes length during electrophoresis, and, therefore, the size of the amplification product^{32,34}. The complementary regions of the MLPA probes range from 19 to 43 nucleotides in length, and the stuffer sequence ranges from 19 to 370 nucleotides, creating a final ligated probe sequence ranging from 130 to 480 nucleotides, which are separated in size by 6 to 9 nucleotides³³. The reference probes, used for normalization of the amount of PCR products from different reactions, hybridize to copy-number stable regions that are not subjected to variations, such as SNPs or structural variations^{29,32}.

The MLPA reaction (Figure 2) begins with denaturation of genomic DNA, at 98°C for 5min, followed by incubation with a mixture of probes that hybridize to single-stranded DNA, at 60°C for 16 to 20 hours, to allow complete hybridization. Then, only if the two half-probes hybridize to contiguous sequences, without a single gap, they are joined together by NAD-dependent DNA ligase, i.e., the ligation reaction occurs, at 54°C³²⁻³⁴. The following dosage-dependent PCR amplification is carried out using only one pair of primers, complementary to generic sequences, whose 5' ends are fluorescently labelled^{32,34}. Thus, PCR does not amplify the target sequences, but the ligated probes³⁴. Therefore, using the same PCR primers, with equal efficiency, different target sequences can be amplified, mitigating amplification issues due to different primer efficiencies³³. Afterwards, PCR products are separated by size and detected through capillary

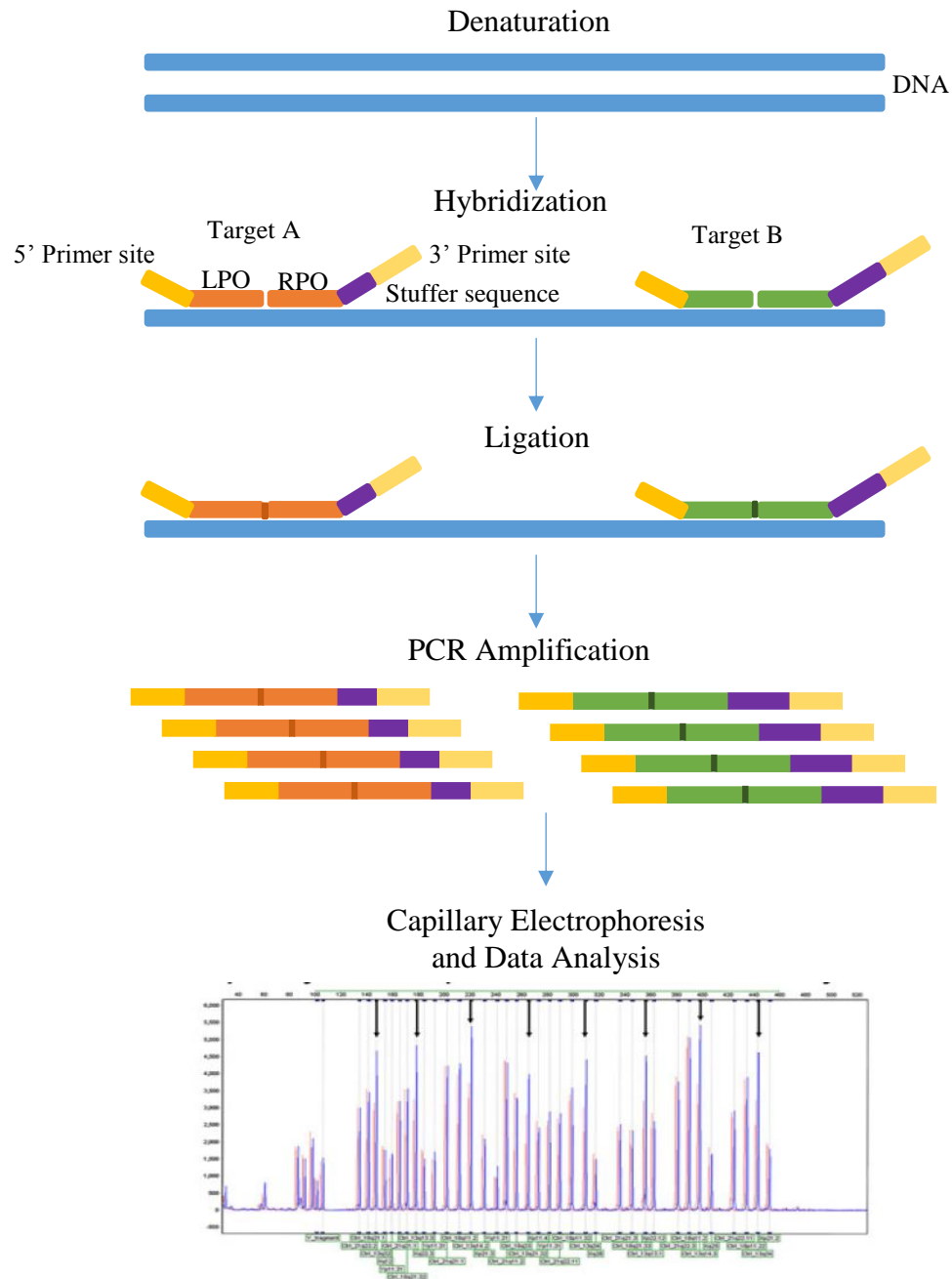


Figure 2 – Schematic representation of the multiplex ligation-dependent probe amplification process.

The MLPA reaction begins with the denaturation of the DNA, followed by the immediate incubation with the MLPA probes, in order to occur hybridization. Then, the ligation reaction occurs, joining the two half-probes. The subsequent PCR reaction occurs using only PCR primers pairs, amplifying the MLPA probes. Afterwards, the PCR products are separated by size and detected by capillary electrophoresis, followed by normalization and data analysis. Adapted from Willis, A. S., Veyver, I. Van Den & Eng, C. M. Multiplex ligation-dependent probe amplification (MLPA) and prenatal diagnosis. *Prenat. Diagn.* 32, 315–320 (2012).

electrophoresis^{29,32}. Each specific probe migrates according to its molecular weight and the resulting electropherograms show PCR-derived-fluorescence-specific peaks that

correspond to each probe³¹. The intensities (height or area) of the peaks are measured, quantifying the amount of PCR product, followed by normalization and comparison to control DNA samples^{31,34}. This indicates the relative amount of target DNA sequence in the input DNA sample, with peak ratios between 0,7 and 1,3 considered normal, ratios above 1,3 or below 0,7 indicating the presence of a gain or a loss of the target sequence, respectively^{33,34}.

The interpretation of the MLPA results is a key step in the application of this methodology for molecular diagnosis of deletions and/or duplications. Results interpretation can be challenging due to different PCR efficiencies among the different probes and sample-to-sample variations. Different strategies for data analysis, such as Coffalyser, have been developed to allow correct interpretation of raw data³⁴.

The main advantages of MLPA are its low cost, reliability, high-throughput and speed, since it can be completed within 24 to 48 hours. Besides, it is relatively simple to implement, requiring minimal training for an experienced technician^{31,33}. Moreover, MLPA can detect small changes, at the level of a single exon. Comparing to another methods, MLPA requires less DNA, is less technically demanding, is faster than Southern blotting, and yields fewer results of unclear clinical significance than quantitative PCR³³.

However, like any dosage technique, MLPA is sensitive to DNA quality, being sensitive to contaminants and DNA degradation, and requiring 100-200ng of DNA for reliable and reproducible results. Furthermore, MLPA is sensitive to the kind of sample that is used for DNA extraction³⁴. It is recommended to compare different MLPA analysis only if they come from the same DNA extraction method, from the same tissue, with control DNA ideally from the same type of source material, and extracted in the same manner as the test sample, in order to reduce variability^{33,34}. MLPA cannot detect copy neutral loss of heterozygosity and may experience problems with mosaicism, tumour heterogeneity, or contamination with normal cells³⁴. The DNA ligase used in the ligation step is sensitive to the presence of mismatches near the ligation site, however, mismatches further away from the ligation site may have little to no effect on the ligation³³. If a pathogenic point mutation or polymorphism not affecting gene function occurs within an MLPA probe-binding site, it might hamper the correct hybridization of the probe, resulting in failure of ligation that will appear as a deletion of a whole exon³⁴. Sometimes, due to

sequence constraints within the exon, probes may target nearby intronic sequences and signal changes observed for these probes may not reflect the copy number of the exon itself³³. Therefore, an independent method must be applied to verify apparent single exon deletions detected by MLPA³⁴.

Polymerase Chain Reaction

The polymerase chain reaction (PCR) technique was developed in 1983, by Kary Mullis, awarded with the Nobel Prize in Chemistry in 1993³⁵. PCR is based on the principle that, through a set of reagents, one can exponentially amplify a chosen region of a DNA molecule *in vitro*, mimicking the naturally occurring cellular process^{36,37}. This mixture of reagents includes a template DNA, multiple copies of a pair of synthesized primers, a heat-tolerant DNA polymerase and a supply of nucleotides³⁷. The chosen primers determine the region to be amplified. The most widely used DNA polymerase is *Taq* DNA Polymerase I, from the bacteria *Thermus aquaticus*, that is naturally occurring of thermal vents and hot springs. This enzyme is thermostable and can resist to high temperatures, where DNA polymerases from other species would denature^{10,37}.

The PCR comprises a sequence of steps that occur in a thermal cycler at different temperatures (Figure 3). It initiates with the denaturation of the template DNA at high temperature, usually around 95°C. The hydrogen bonds that bind the two strands of the double-stranded DNA break and single-stranded DNA molecules are formed^{10,37}. This step is followed by the annealing, i.e. the hybridization, of the oligonucleotide primers to their complementary sequences in the DNA template, at a lower temperature, around 50

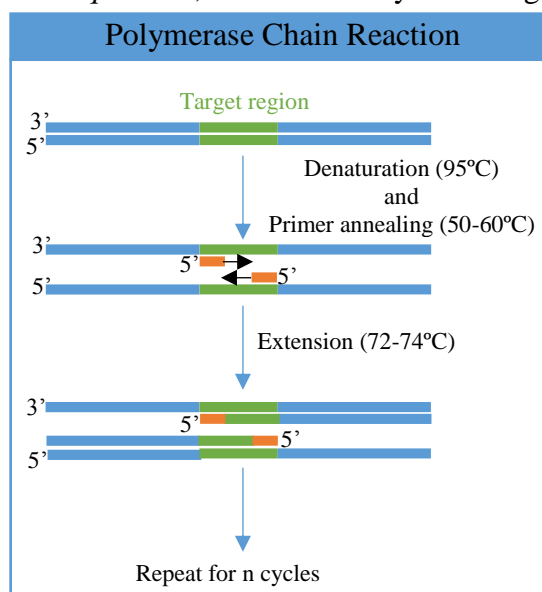


Figure 3 – The basic steps in the polymerase chain reaction.

PCR consists in the repetition of the cycle that comprises three main phases: denaturation of the dsDNA at high temperatures; annealing of the primers to their complementary sequence in the DNA template; and extension of the chains through DNA polymerase synthesis activity. Adapted from Griffiths AJF. *Introduction to Genetic Analysis*. 10th ed. Winslow S, editor. W. H. Freeman & Company; 2012.

to 60°C. Each one of the primers binds to a different end of the gene or region to be amplified, in opposite DNA strands with their 3' ends pointing at each other³⁷. At this temperature, the single stranded DNA could be re-joined, but the excess of the primers, that anneal specifically to each strand, prevents this¹⁰. The temperature is raised until the optimal temperature of the *Taq* polymerase in use, around 72-74°C³⁷. The *Taq* polymerase binds to the ends of the primers, allowing for synthesis of the complementary new DNA strands from the primer, the extension phase^{10,37}. At this point, the generated molecules have identical 5' ends, but different 3' ends, due to the randomness of the DNA synthesis finish, forming the "long products"¹⁰. Then, this cycle repeats itself many times, exponentially increasing the number of DNA molecules, denaturing the "long products" and forming "short products", where the 5' and 3' ends are defined by the primers annealing positions. These "short products" are identical to each other and ideally double at each cycle, while the reagents are being depleted.

1) Real-time Quantitative PCR

The number of DNA molecules present in the starting mixture directly affects the quantity of product synthesized in a given number of PCR cycles. Eventually, the exponential rate of amplification of the PCR reaction stops due to inhibitors of the polymerase reaction in the template, reagent limitation or accumulation of pyrophosphate molecules, generating variable amounts of PCR product. At this point the quantitation is not reliable, therefore the extrapolation should be made at the exponential phase of the reaction^{35,38}. Initially, these comparisons were made through agarose gel electrophoresis that, although simple and easy to perform, is imprecise. Nowadays, the quantitation is carried out by real-time quantitative PCR (qPCR), that allows the measurement of the product synthesis over time, during the PCR cycles³⁵.

In 1993, the first publication describing qPCR was published³⁵. Quantitative PCR was developed for DNA quantitation, allowing specific and sensitive quantitation of nucleic acids^{39,40}. It is advantageous over other methods of gene expression analysis, since: (a) it does not require post-PCR manipulation, reducing contamination risk; (b) it has low instrumentation and consumable costs, a fast turnaround and assay development time, and an open format; and (c) it is highly sensitive, requiring minimal amounts of input DNA^{41,42}.

It is widely used in biomedical research and diagnosis, particularly in mRNA expression studies, DNA copy number measurements in genomic or viral DNAs, allelic discrimination assays, expression analysis of specific splice gene variants, as well as other scientific fields, such as water, food and feed testing^{38,40}. Furthermore, qPCR has been used to validate aCGH results, such as the ones regarding CNVs, in several studies^{22,43–46}.

During qPCR, the thermocycler collects fluorescence emission data that are analysed by the computer software, which constructs amplification plots, in the form of a sigmoidal amplification curve (Figure 4)^{38,41}. When analysing these plots, it is important to recognize some important nomenclature related to PCR. First of all, the baseline is the PCR cycles where the fluorescence signal remains beneath the limits of detection of the thermocycler, usually until cycle 15. The software calculates the threshold based on the standard-deviation of the average signal of the baseline signal, although it can be manually altered. It is considered a real signal when a fluorescent signal is above

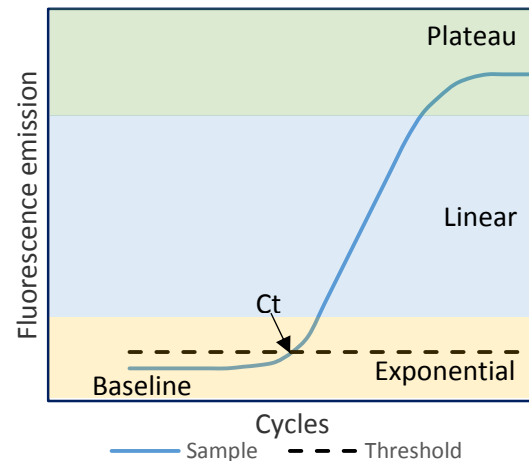


Figure 4 – Model of a single amplification plot illustrating the nomenclature commonly used in qPCR.

The PCR goes through three phases, the exponential, the linear and the plateau phases. The PCR product increases throughout the cycles, increasing the fluorescence emission and generating a sigmoidal curve. Adapted from Arya, M., Shergill, I. S., Williamson, M. & Gommersall, L. *Basic principles of real-time quantitative PCR. Expert Rev Mol Diagn* 5, 209–219 (2005).

the threshold, and it can be used to define the threshold cycle (Ct) for a sample^{38,42}. The Ct, or the quantification cycle (Cq), is the fractional cycle at which the reporter fluorescence is higher than the threshold, being essential for accuracy and reproducibility. It is inversely proportional to the initial amount of input DNA, and it always occurs during the exponential phase of the amplification, in the early cycles of the reaction. As the PCR continues, the amplification rate decreases until it reaches the plateau phase, where the fluorescence stabilizes^{38,41}.

2) *Experimental Design*

Although it might seem a simple technique, the PCR experiment design must be well thought and planned, with all the assays run under the same conditions⁴⁷. All the steps can limit efficiency, sensitivity and accuracy of the technique. In qPCR the aim is to minimize the interference with the doubling of the target amplicon at each cycle, in order to maximize efficiency³⁹. PCR efficiency, often expressed in percentage (%), is defined by Bar and colleagues as “the fraction of double-stranded DNA molecules that is copied at a given cycle”, with an efficiency of 100% representing a perfect doubling of all DNA molecules⁴⁰. PCR efficiency is often affected by MgCl₂, primer and probe concentrations⁴⁷. qPCR assays must be appropriately designed in order to amplify target DNA with at least 90% efficiency⁴⁸.

The optimization of the amplification step is essential and can be achieved through modifications of the nucleic acids preparation protocol and the choice of adequate primers, buffers and cycling conditions³⁹. The nucleic acids purity of samples, frequently obtained from fixed archival, fresh cell culture or blood products, is highly important in order to have reproducibility. In order to determine DNA purity and the presence of PCR inhibitors, if possible, each DNA sample should be tested with a standard curve⁴⁷.

The primers design is of extreme importance for the success of a PCR, because incorrect primers can result in no amplification at all or in non-specific amplification of multiple fragments. The primers sequence must flank and be complementary to the target region on the DNA template, with their 3' ends pointing towards one another. The size of the primer is also of great importance to achieve specific hybridization. On one hand, a primer that is too short might hybridize to non-target sites and produce undesired fragments. On the other hand, a long primer hybridizes at a slow rate, and complete hybridization does not occur in adequate time, reducing the efficiency of the PCR. Thus, primer's optimal length is between 15 and 20 nucleotides, with a GC content of 20-80%, and the melting temperature (T_m) for both primers of the pair should be similar ($\Delta T_m \leq 2^\circ\text{C}$). In order to maximize the specificity of primers, it is recommended for each primer to have only one or two Gs or Cs within the last 5 nucleotides, at the 3' end. The generated DNA fragment, the amplicon, ideally should be less than 1kb in length, in order to maintain the amplification efficiency, obtain consistent results and be tolerant to reaction conditions. When the utilization of probes is required, probe design also follows a set of

specifications. In order to guarantee that the probe is fully hybridized during primer extension, it is desirable that the probe T_m is 8-10°C higher than the T_m of the primer^{10,38}.

Regarding to the temperature conditions, the annealing temperature (T_a) is the most important, once it can affect the specificity of the reaction. At high temperatures, the hybridization cannot occur, and the primers and template DNA remain dissociated. In contrast, at low temperatures mismatched hybrids are frequent and stable, producing non-target amplification. Hence, the annealing temperature must be low enough to allow hybridization, but high enough to prevent the formation of mismatched hybrids. In order to estimate this “perfect” temperature, one should calculate the T_m of the primer-template hybrid, at which they dissociate, that is 1-2°C higher than the annealing temperature. Therefore, the primers should have identical T_m so the annealing temperature is adequate for both. The T_m can be determined experimentally or, more frequently, it can be calculated from the formula:

$$T_m (^{\circ}\text{C}) = 4 \times (\text{G} + \text{C}) + 2 \times (\text{A} + \text{T})$$

in which (G + C) is the number of G and C nucleotides in the primer sequence, and (A + T) is the number of A and T nucleotides¹⁰. The hot start consists of starting the PCR reaction at high temperature, in order to eliminate unwanted hybridization that is frequent in the first cycle. This increases sensitivity and reproducibility of the amplification and quantitation³⁹.

As previously described, quantitation should be performed in the exponential phase of the PCR, frequently somewhere between the 15th and the 30th cycles. These are usually associated with the linear range of amplification, where the quantitated amount of amplified target is proportional to the initial amount of target molecules. Often, this linear range of amplification is defined through the testing of control samples or standards³⁹.

3) Normalization and Reference Genes

During qPCR experiments, specific errors are introduced due to minor differences in the starting amount, the quality of DNA, or the PCR amplification efficiency. In order to minimize these errors and correct non-specific variation, data from qPCR should be submitted to appropriate normalization. Usually, reference genes in CNVs studies, or

housekeeping genes in the case of expression studies, are selected in the surrounding area or on the same chromosome as the disease gene⁴². While a housekeeping gene should be theoretically expressed at a constant level in different tissues of an organism, at all stages of development, and in different experimental conditions, the reference gene should not have CNVs described in the literature. Generally, the housekeeping genes are indispensable for the cellular regular function. These internal reference or housekeeping and the target gene are then simultaneously amplified, with the assumptions that their copy number is equal or their expression is similar between all samples and resistant to experimental conditions, since it undergoes all steps of the qPCR with the same kinetics as the target gene^{35,38}. The choice of the reference gene must be made with regard to the specificities of each experiment, since it significantly influences the results reliability. However, there has not been identified an unequivocal reference gene yet and the use of several simultaneous reference genes has been suggested, with their mean quantitation used for normalization³⁸. This approach is useful when the housekeeping gene is affected by the experimental design and treatments or when comparing different tissue types and provides a more robust, reliable and accurate quantitation^{35,42}. Some of the commonly used reference genes include *β-actin*, *GAPDH*^{35,38,49,50}, *ZNF80*^{41,51–55} or *GPR15*^{41,52,54}.

4) Amplicon Detection

During the qPCR experiment, the product accumulation may be followed by one of several different chemistries, including double stranded DNA specific binding dyes, i.e. dsDNA-intercalating agents, or fluorescent probes, such as hydrolysis probes, dual hybridization probes and molecular beacons^{38,41}. It is important to select the adequate method for a specific PCR assay, according to its objective.

The dsDNA-intercalating agents are nonsequence-specific fluorogenic DNA-binding dyes that intercalates into dsDNA. It is the simplest method, relatively cheap, and includes SYBR[®] Green I and EvaGreen[®]. When bounded to double-stranded DNA, the dye gives a fluorescent signal, measuring the total amount of double-stranded DNA at the end of the elongation step of each PCR cycle. However, it might overestimate the true amount of product because it binds to all dsDNA, such as non-specific PCR products and primer-dimers that sometimes are formed. In order to increase the reaction specificity, melting

curves should be generated and compared. The melting peak at the melting temperature of the amplicon differentiates it from the artifacts with lower melting temperatures and broader smaller peaks^{10,38}. EvaGreen[®] outperforms SYBR[®] Green, achieving high reaction efficiencies and giving higher and sharper peaks in melt curve analysis, due to the fact that it can be used at relatively high concentrations^{56,57}. Also, EvaGreen[®] is less inhibitory to PCR than SYBR[®] Green and has a relatively low tendency to cause nonspecific amplification. Moreover, EvaGreen[®] is very stable and spectrally compatible with existing PCR instruments⁵⁷.

The hydrolysis probes require a forward and a reverse primer, and their efficiency is dependent on the 5' to 3' exonuclease activity from *Taq* polymerase, for example. The fluorogenic non-extendable “TaqMan” probe has a covalently bonded fluorescent reporter dye attached at its 5' end and a quencher dye attached to the 3' end. When intact, the quencher is close to the reporter dye, decreasing the fluorescent signal, through fluorescence resonance energy transfer (FRET). However, during the real-time quantitative TaqMan[®] assay, the fluorogenic probe hybridizes with the target sequence and, during the extension phase, is cleaved by the 5' nuclease activity of *Taq* polymerase. The cleavage removes the probe from the target strand and separates the dyes, increasing the fluorescence of the reporter dye. At each cycle, more and more probes are cleaved, increasing the fluorescence intensity in a way that is directly proportional to the amount of generated fragments³⁸.

The method of dual hybridization probes requires two different oligonucleotides specific for the PCR product probes, in a tandem-like manner. The downstream probe carries a donor fluorophore at its 3' end and the upstream probe has an acceptor fluorophore attached to its 5' end. Each of the probes anneals with its respective target sequence in a head-to-tail manner, after denaturation. This way, the two fluorophores are brought closer in spatial proximity, allowing FRET. The donor dye transfers energy to the acceptor, that dissipates fluorescence at a different wavelength. As a consequence, this method is highly specific because the fluorescence only occurs when the two independent probe hybridize correctly to their target sequences^{38,58}.

In the same way as the hydrolysis probes, the molecular beacons have a fluorescent reporter dye attached at its 5' end and a quenching compound attached to the 3' end.

However, when near or below the annealing temperature and free in solution, the intact probe has the two ends base pairing to one another due to short complementary sequences, forming a hairpin or a stem-loop structure. As a result, the quencher is next to the reporter dye, decreasing the fluorescent signal, based on the FRET principle. During the annealing step, the loop portion, complementary to the target sequence hybridizes, causing a conformational change, and the stem is cleaved. Then, the dyes are separated and the quencher no longer decreases the reporter dye fluorescence, generating a fluorescent signal. At each cycle of the PCR, the molecular beacons rehybridize to the target sequence for fluorescence emission, indicating the amount of accumulated amplicon^{10,38,58}.

5) Quantitation Methods

One of the methods to quantify real-time PCR results is the standard-curve or absolute quantitation, often used to measure a small number of genes in a few or many samples⁴⁷. It is based on the plotting of a standard curve, constructed with the logs of copy numbers from standards with known quantities of initial DNA versus their corresponding Cts, which generates a straight line. Then, the Ct of the test samples is measured and compared with the standard curve, in order to determine the initial target amount³⁸. In other words, the amount of product amplified from the test sample is compared with the amount of product amplified from standards with known quantities of initial DNA¹⁰.

Another method of quantitation in qPCR is the relative quantitation or Delta Delta Ct method ($2^{-\Delta\Delta Ct}$ method), which requires a reference control and a

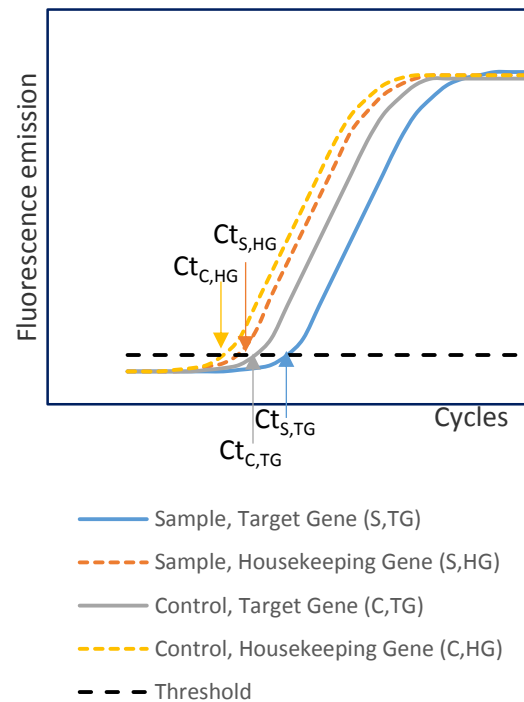


Figure 5 – Model of an amplification plot illustrating the mathematical basis of the $2^{-\Delta\Delta Ct}$ method.

This method allows relative quantitation through the measurement of cycle thresholds from the target and housekeeping genes of the test and control samples. Adapted from Vanguilder, H. D., Vrana, K. E. & Freeman, W. M. Twenty-five years of quantitative PCR for gene expression analysis. *Biotechniques* 44, 619–626 (2008).

housekeeping gene (Figure 5). First of all, if this method is applied, the results only are considered valid and reliable if the amplification efficiencies of the housekeeping and target genes are very similar and at or above 90%^{38,40}. To guarantee that, a 10-fold serial dilution of a positive control template can be performed, followed by the plotting of the Ct as a function of \log_{10} (concentration of template). The trend line slope (M) gives the PCR efficiency, through the function $Efficiency = 10^{1/-M} - 1$, with $-3,32$ indicating an efficiency of 100%⁴⁷. The relative expression levels of a target are calculated relative to a reference control (calibrator) through mathematical equations. The target amount of the sample is normalized to an endogenous housekeeping gene and relative to the normalized control. It is calculated by the formula³⁸:

$$2^{-\Delta\Delta Ct},$$

$$\text{where } \Delta\Delta Ct = \Delta Ct_{sample} - \Delta Ct_{control},$$

$$\text{and } \Delta Ct_{sample/control} = Ct_{target\ gene} - Ct_{housekeeping\ gene}.$$

Objectives

The present work describes the development and validation of a qPCR method for CNVs detection. A qPCR-based methodology was developed to search for large deletions and/or duplications in genes in two situations: a) sequences which are not covered by aCGH or MLPA kits and b) confirmation or exclusion of previous MLPA and aCGH results.

To accomplish that, initially the methodology was validated using samples with known results for the genes *MECP2*, *NF1* and *PARK2*. Then, the method was developed in order to search for CNVs upon request. At the moment, 33 genes were assessed. The work flow begins with the selection of regions and primers design, followed by the primers validation. When the primers are validated, the samples are subjected to qPCR and the results analysed.

Methods

Samples

For validation of the study, 3 samples with normal copy number, 1 sample with a known deletion and 1 sample with a known duplication, all regarding the *MECP2* gene, were used. Also, 5 samples with normal copy number for the tested fragment, 1 sample with a known deletion and 1 unknown sample were used for each *NF1* and *PARK2* genes. All samples were extracted from blood (EDTA) and studied previously by another method, such as MLPA, aCGH or other.

For the development of the study 36 samples, extracted from blood (EDTA), were used as calibrators and/or normal samples. The calibrator samples were selected from genomic DNA samples with prior diagnosis of another disease without relation to CNVs of the tested fragment, which were beforehand studied by aCGH or MLPA. At first, in some cases, calibrator samples were commercial normal genomic DNAs, used in NGS or aCGH, and pools of 3 samples used for MLPA. After several tests it was decided that calibrator samples should be a pool of 3 normal samples. When the tested fragment was from a gene of the X chromosome, the calibrators were male pools if the test sample was male or female pools if the test sample was female. Also, 32 unknown samples, extracted from blood (EDTA) or, in some cases, purified genomic DNA, were tested for several genes.

The negative control consisted of water, without template DNA, in order to check for primer-dimer and contaminations. All samples (Table S1, ANNEX I) were diluted with TE buffer to a concentration of $20\text{ng}/\mu\text{L} \pm 1,5\text{ng}/\mu\text{L}$, and quantified in EPOCH (BioTek).

Selection of Regions and Primers Design

One region of the *ZNF80* gene and another of the *GPR15* gene, having no CNVs described in the literature, were used as reference genes for normalization, during the relative quantitation^{51–53}.

The regions to be amplified in the test samples were selected based on the described gross deletions and gross insertions of the gene, recurring to The Human Gene Mutation Database (HGMD; <http://www.hgmd.cf.ac.uk/>), in order to ensure the detection of small deletions and duplications. The genes of interest were searched on the Ensembl Genome

Browser (<http://www.ensembl.org/>), with the organism “human” selected. Each gene sequence was downloaded in FASTA format and converted into Microsoft Office Word format for primer design.

Primers were designed with the online program Primer3Plus (www.bioinformatics.nl/cgi-bin/primer3plus/primer3plus.cgi), according to the following criteria: primer size of 18/20/22bp (minimum/optimal/maximum); GC content between 40 and 60%; T_m of 58/60/62°C (minimum/optimal/maximum); amplicon size of 100/150/200bp (minimum/optimal/maximum). When not possible, primers were designed manually through the software Alamut Visual v. 2.8 rev. 1 (©2015 Interactive Biosoftware), following the same specifications as for Primer3Plus. The selected primers were analysed on the online program SNPCheck v3 (<http://secure.ngml.org.uk/SNPCheck/snpcheck.htm>), to verify that these did not target SNPs. The primers structure analysis, such as primers complementarity, hairpin formation and dimers, was made through the online program Oligo Analyzer 3.1 (<http://eu.idtdna.com/calc/analyzer>), using default settings for qPCR, with the exclusion criterion of $\Delta G \leq -9,0$ kcal/mol and the software Oligo Analyzer 1.0.2 (Copyright© 2000-2002 Teemu Kuulasmaa), with the exclusion criterion of $\Delta G \leq -6,0$ kcal/mol. To ensure primer specificity, primer sequences were run in the online program Primer search 2.52 (<http://bisearch.enzim.hu/>) and in the UCSC *In Silico* PCR online tool (<http://genome.ucsc.edu/cgi-bin/hgPcr>), which also gave primers melting temperatures. The secondary structure of the amplicon sequences was predicted with the online program DNA Folding Form from The mfold Web Server (<http://unafold.rna.albany.edu>), using default settings and a temperature of 60°C, with the exclusion criterion of $\Delta G \leq -7,0$ kcal/mol. In order to predict the melting curve for each fragment, its sequence was inserted in the web-based application uMeltSM – DNA Melting Curve Prediction (<https://www.dna.utah.edu/umelt/um.php>).

The designed primers are summarized in Table S2 (ANNEX II); primers pairs for the *ZNF80*, *MECP2*, *PLCB1*, *PARK2* and *NF1* genes were supplied by Sigma-Aldrich and the remaining were supplied by Invitrogene, due to financial constraints.

Empirical Validation of Primers

After *in silico* testing of primers, an empirical validation was performed, similar to the one described by D'haene and colleagues, in order to optimize primers⁴¹. To estimate qPCR efficiency, the standard curve is the most reliable and robust approach, broadly accepted by the scientific community⁴⁸. A human normal genomic DNA dilution series (1:2 with 5 dilution points of 26ng/μL, 13ng/μL, 6,5ng/μL, 3,25ng/μL and 1,625ng/μL and a no-template control) was prepared and amplified. The concentrations of the dilution series were set in order to extend over the anticipated range of interest (18,5 – 21,5ng/μL) by at least 20%⁴⁸. Assays were performed in duplicate, in a 20μL reaction volume, containing 4μL of 5x HOT FIREPol® EvaGreen® qPCR Mix Plus, 1μL of gDNA, 0,1-1,0μL of forward and reverse primers at an initial concentration of 10nM (final concentration of 200nM) and DEPC Treated Water (Ambion, Life Technologies) up to the reaction volume. Reactions were performed in 0,1mL Strip Tubes in a 72-well rotor using the Rotor-Gene Q (Qiagen, Germany) detection system. Cycling conditions were 95°C for 15min, for initial activation step, followed by 40 cycles of 95°C or 99°C for 15sec, 60°C for 20sec and 72°C for 20sec. A standard curve was generated, with the evaluation of the amplification efficiency, coefficient of determination (R^2) and slope. The PCR efficiency was considered satisfactory when between 90% and 110%, although in some cases an efficiency above 80% was accepted, and the R^2 was considered suitable when not lower than 0,98, preferably over 0,99⁴¹. Afterwards, a melt curve analysis was performed to check the specificity of the PCR reactions. The Ct values were extracted and analysed with the Rotor-Gene Q software, version 1.7.94.

The PCR programme with a melting temperature of 95°C was used as standard. When the fragment melting curve prediction by the uMelt software was near or over 95°C, the PCR program with a melting temperature of 99°C was used for validation. Also, if a melting curve of a fragment first tested at 95°C was highly close to 95°C or the melting was incomplete, the same fragment was validated with a melting temperature of 99°C. When the efficiency was lower than 80% or higher than 110%, the primers volume was increased or reduced, respectively, in the following validation run, until it was validated.

qPCR Assays for CNVs Detection

All real-time qPCR assays were performed in a 20 μ L reaction volume, containing 1 μ L of genomic DNA at an initial concentration of 20ng/mL, 4 μ L of 5x HOT FIREPol[®] EvaGreen[®] qPCR Mix Plus, 0,1-1,0 μ L of forward and reverse primers at an initial concentration of 10nM (final concentration 200nM) and DEPC Treated Water (Ambion, Life Technologies) up to the reaction volume. Reactions were performed in 0,1mL Strip Tubes in a 72-well rotor using the Rotor-Gene Q (Qiagen, Germany) detection system. Cycling conditions were 95°C for 15min, for initial activation step, followed by 40 cycles of 95°C or 99°C for 15sec, 60°C for 20sec and 72°C for 20sec. Primers volume and cycling conditions were used according to the ones used in the primers validation, when optimized.

During validation of the method, the *MECP2* experiment contained 2 calibrator samples (in duplicate), a sample with normal copy number (in duplicate), a sample with a known deletion (in duplicate), a sample with a known duplication (in duplicate), and a NTC (in duplicate). The experiments regarding the *NF1* and *PARK2* genes contained 2 calibrator samples (in triplicate), a sample with normal copy number (in triplicate), a sample with a known deletion (in triplicate), an unknown sample (in triplicate), and a NTC. Throughout the method development, each experiment contained 3 calibrator samples (in triplicate), a sample with normal copy number (in triplicate), at least, a test sample (in triplicate), and a NTC. In order to test genes located at the X chromosome, the 2 calibrator samples (in triplicate) and the sample with normal copy number (in triplicate) were pools of male samples only, since the test sample was male; also, we used a pool of female samples as a positive control (in triplicate), as well as a test sample (in triplicate), and a NTC.

The copy number level of target genes was normalized to the *ZNF80* or the *GPR15* gene. After PCR amplification, a melting curve was generated for each PCR product and analysed in order to ensure amplicons specificity. Data collection and analysis was performed through Rotor-Gene Q software, version 1.7.94, with the Ct values exported to Microsoft Office Excel.

Data Analysis and Statistics

The data analysis was performed using the Microsoft Office Excel software, based on the method described by Hoebeeck and colleagues⁵². Reaction wells with obvious PCR reaction failure or clear outlier values (difference between Ct and mean Ct greater than 0,5) were excluded from data analysis. Copy number alterations were calculated according to the Delta Delta Ct method ($2^{-\Delta\Delta C_t}$) and the samples were scored as normal, deleted or duplicated based on the scoring limits established. A haploid copy number of 1 is expected for a normal sample, a value of 0,5 for a sample with a deletion and a value of 1,5 for a sample with a duplication^{22,59,60}.

The expected cut-off values used were 0,7 for deletion upper limit⁵¹⁻⁵³, 0,8 for normal lower limit⁵¹⁻⁵³, 1,2 for normal upper limit⁵³ and 1,25 for duplication lower limit⁵⁰. As such, fragments with a haploid copy number below the deletion upper limit were scored as deleted, while fragments with a haploid copy number between the normal lower and upper limits were scored as normal, and finally fragments with a haploid copy number above the duplication lower limit were scored as duplicated. A fragment with an ambiguous haploid copy number was reanalysed.

To determine the accuracy and to evaluate the precision of the qPCR approach, the haploid copy number values and their standard deviations for the deleted vs. control samples and duplicated vs. control samples were compared. In order to evaluate the equality of the two variances, a F test was performed (p-value < 0,05). If the two variances were not significantly different, then the two-sample t test for independent samples with equal variances was used; otherwise, a two-sample t test for independent samples with unequal variances was selected. The two-sample *t-test* was performed to evaluate if the copy numbers are significantly different between deleted and control samples as well as between duplicated and control samples (p-value < 0,05).

At the end of all tests, based on the observed haploid copy number and the standard deviation, the limits for scoring a deletion, a normal copy number or a duplication were assessed. The mean value of the haploid copy number in deleted fragments plus two times the standard deviation was used as upper limit for scoring a deletion. For scoring a normal fragment, the mean value of the normal haploid copy number minus two times the standard deviation was used as lower limit and the mean value of the normal haploid copy number

plus two times the standard deviation was used as higher limit. Similarly, the mean value of the haploid copy number in duplicated fragments minus two times the standard deviation was used as lower limit for scoring a duplication.

The qPCR results from the method validation were compared to previous results of MLPA, aCGH, Sanger sequencing and NGS, in order to evaluate the sensitivity (false-negative results), specificity (false-positive results) and accuracy (true-value determination) of the qPCR approach.

Results and Discussion

Method Validation

In order to validate the planned methodology, qPCR for the *MECP2*, *NF1* and *PARK2* genes were performed. The primers were designed according to the CNVs detected in the samples previously studied by another method and validated through the generation of a standard curve and melt curve analysis. The standard curve allowed the efficiency assessment of each primers' pair (Figure 6).

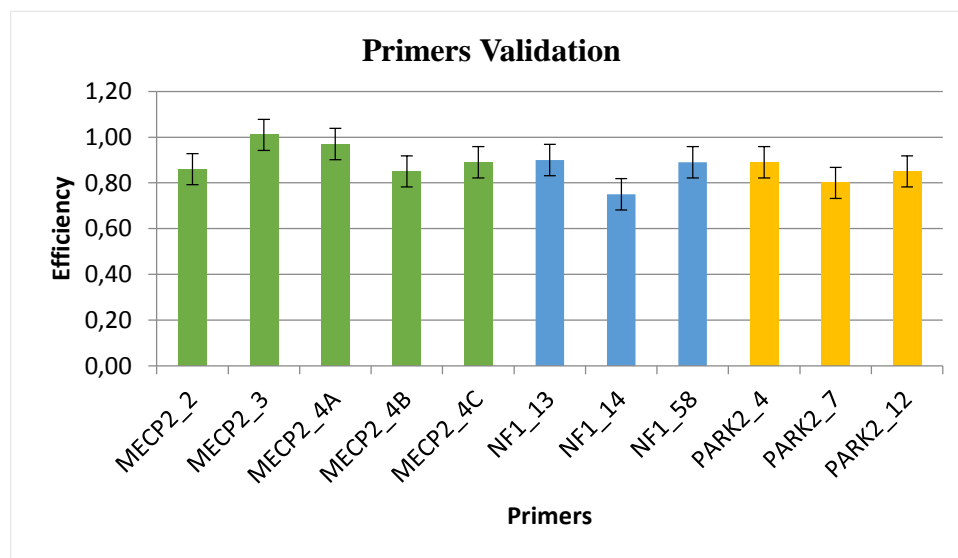


Figure 6 - Efficiency of the primers pairs for the *MECP2*, *NF1* and *PARK2* genes, used in the methodology validation.

The mean efficiency of the primers pairs was $0,88 \pm 0,07$, with the primers pair for exon 14 of the *NF1* gene being the one with the lowest accepted efficiency (0,75). The primers pair *MECP2_4B* was discarded from the relative quantitation analysis, since it was considered not specific through the melt curve analysis.

1) The *MECP2* gene

Regarding the *MECP2* gene, 3 samples with normal copy number (calibrators and samples A1), 1 sample with a known deletion (sample A4) and 1 sample with a known duplication (sample A5), were used. The *MECP2* gene encodes a methyl-CpG binding protein, which is likely to be involved in transcriptional regulation. The most frequent mutation in the *MECP2* are point mutations, small insertions or deletions⁵⁵. Mutations in this gene are associated with Rett syndrome (MIM [312750](#)), as well as with a severe neonatal form of encephalopathy (MIM 300673) and with X-linked syndromic mental retardation (MIM 300055, MIM 300260). The efficiency and specificity of each primers pair was evaluated through the generation of standard curves from a dilution series of DNA from two of the samples with normal copy number and a melting curve, respectively. Although primers MECP2_2 and MECP2_4C had efficiencies slightly below 90%, the initial cut-off value for acceptance, their melting curves showed specificity, and they followed to quantitative assay (Figure 6). The primer pair MECP2_4B was discarded from the subsequent quantitative assay, since it had a low efficiency in the standard curve from primers validation and the melt curve analysis showed that it was not specific.

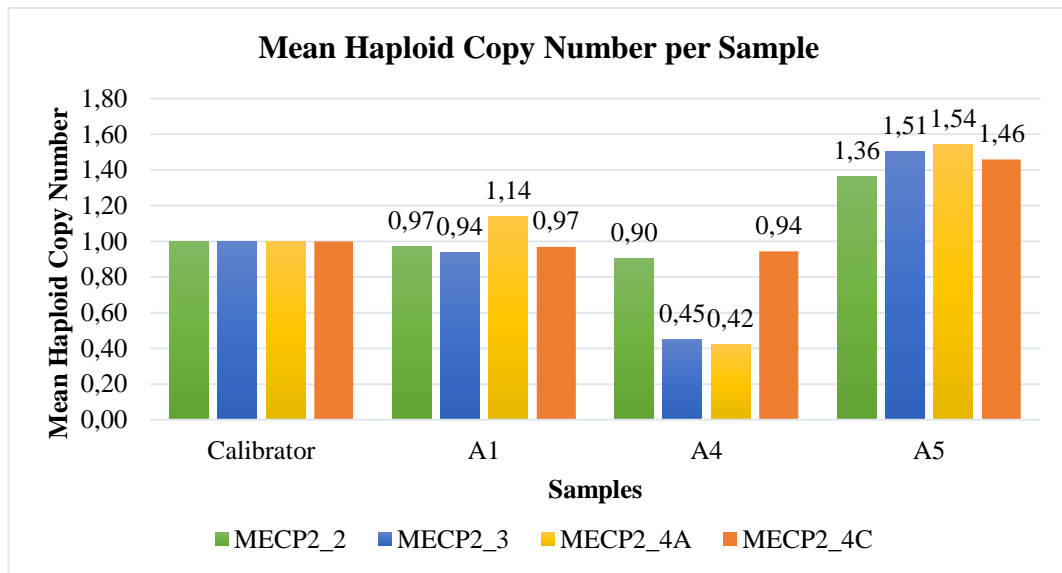


Figure 7 - Relative quantitation of the *MECP2* gene, during method validation.

Sample A1 had a normal haploid copy number (1.01 ± 0.08) for every primers pair. Sample A4 presented a normal copy number (0.92 ± 0.02) for exon 2 and the end of exon 4, as well as a heterozygous deletion (0.44 ± 0.01) between exon 3 and part of exon 4. Sample A5 had a whole gene heterozygous duplication (1.47 ± 0.07).

The results from the quantitative PCR (Figure 7) were concordant with the previous findings by aCGH and MLPA. Sample A1 had a normal haploid copy number ($1,01 \pm 0,08$) for every primers pair as expected, and MLPA was negative for deletions or duplications. Sample A4 showed a heterozygous deletion of exon 3 in the aCGH study and a heterozygous deletion of exon 3 and part of exon 4 in the MLPA. qPCR of this sample presented a normal copy number ($0,92 \pm 0,02$) for exon 2 and the end of exon 4, as well as a deletion ($0,44 \pm 0,01$) between exon 3 and part of exon 4. Also, sample A5 had a whole gene heterozygous duplication ($1,47 \pm 0,07$), in agreement with the heterozygous duplication detected by MLPA. Since the relative quantitation results were in agreement with previous results, the efficiency cut-off value for primers acceptance was redefined to 80%. However, primers efficiency was still preferred between 90 and 110%.

2) *The NF1 gene*

Subsequently, the *NF1* gene was tested, by analysing 3 samples with normal copy number, 1 sample with a known deletion and 1 unknown sample. The unknown sample, blinded for qPCR testing, was previously tested at another lab by NGS and qPCR, which reported a duplication of exon 13; however, the results of MLPA at this lab were negative for deletions or duplications of the *NF1* gene. The Neurofibromin 1 (*NF1*) gene (OMIM* 613113) is a tumour suppressor, located at 17q11.2 locus, which contains 57 constitutive coding exons and 3 alternative spliced exons over 280kb^{61,62}. *NF1* is a negative regulator of the oncogene *Ras*, being a Ras-GTPase activating protein and its loss is associated with increased formation of Ras-GTP leading to increased downstream signalling^{63,64}. Heterozygous mutations in this gene cause neurofibromatosis type I (MIM 162200). Even though exon 14 primer pair had a low efficiency of 75% (Figure 6), all primers were considered validated, since the melt curve analysis indicated amplification of specific fragments.

Sample A10 had a normal haploid copy number ($0,99 \pm 0,04$) for every pair of primers, as predicted, since it was a sample with a positive result for DMD deletion, and therefore it was not expected to have another deletion/duplication. Sample A11 showed a heterozygous deletion of the entire gene in the MLPA study. qPCR of this sample presented a heterozygous deletion ($0,65 \pm 0,03$) of all tested fragments. Furthermore, the

blinded sample A12 showed a normal copy number ($0,99\pm0,07$), discordant with the results from another lab, however in agreement with the MLPA results. As such, the duplication of exon 13 was ruled out as a false-positive result.

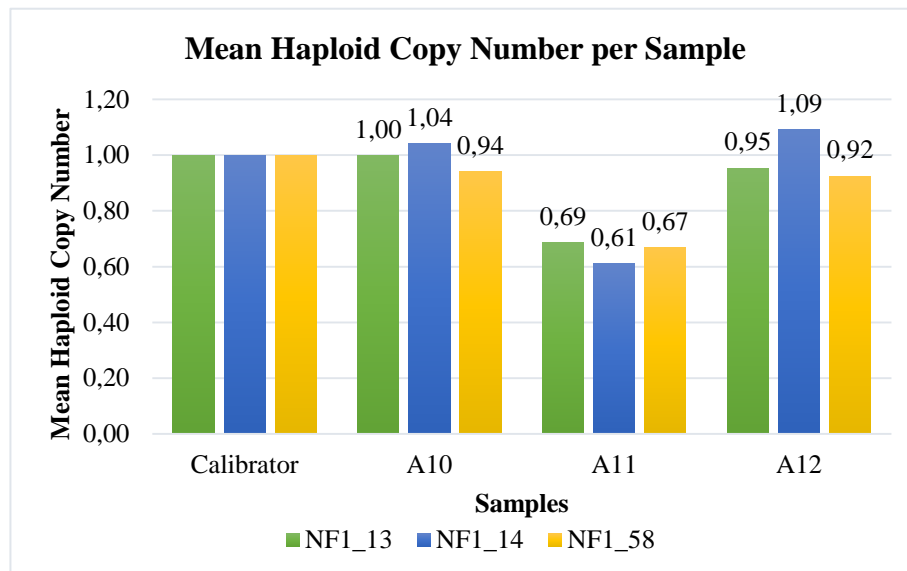


Figure 8 - Relative quantitation of the *NF1* gene, during method validation. Sample A10 had a normal haploid copy number ($0,99\pm0,04$) for every primers pair. Sample A11 presented a heterozygous deletion ($0,65\pm0,03$) of all tested fragments. Sample A12 showed a normal copy number ($0,99\pm0,07$).

3) The *PARK2* gene

In order to test for the *PARK2* gene, 3 samples with normal copy number, 1 sample with a known deletion and 1 unknown sample, were used. The unknown sample was previously tested by MLPA, which showed a heterozygous deletion of exons 4 to 7, but it was blinded for qPCR testing. The *PARK2* gene (OMIM* 602544) encodes an E3 ubiquitin ligase, being located on chromosome 6, locus 6q25.2-q27^{65,66}. Autosomal recessive juvenile Parkinson disease-2 (MIM 600116) is caused by homozygous or compound heterozygous mutation in this gene. *PARK2* encompasses a genomic region of 1.3Mbp, consisting of 12 exons, and its 4.5kbp transcript contains a 1,395 bp open reading frame⁶⁵. *PARK2* is located within FRA6E, one of the most unstable common fragile sites of the human genome⁶⁵. All primers were considered validated, since their efficiency was above 80% (Figure 6) and the melt curve analysis indicated specific fragments amplification.

Sample A10 had a normal haploid copy number ($1,02\pm0,01$) for every primers pair as expected, since it was a sample with a positive result for DMD deletion. Sample A13

showed a compound heterozygous deletion of exons 3 to 4 and 3 to 6 in the MLPA study and a sequencing failure of exons 3 and 4 after Sanger sequencing. qPCR of this sample presented a normal copy number (1.03 ± 0.05) for exons 7 and 12, as well as a false homozygous deletion (0.00 ± 0.00) of exon 4, since it cannot differentiate between a homozygous and a compound heterozygous deletion. Moreover, the blinded sample A14 had a heterozygous deletion (0.55 ± 0.09) of exons 4 and 7, but it had a normal copy number for exon 12, in agreement with the posteriorly known MLPA results. Therefore, the qPCR results were concordant with the previous findings for this gene either from MLPA or Sanger Sequencing.

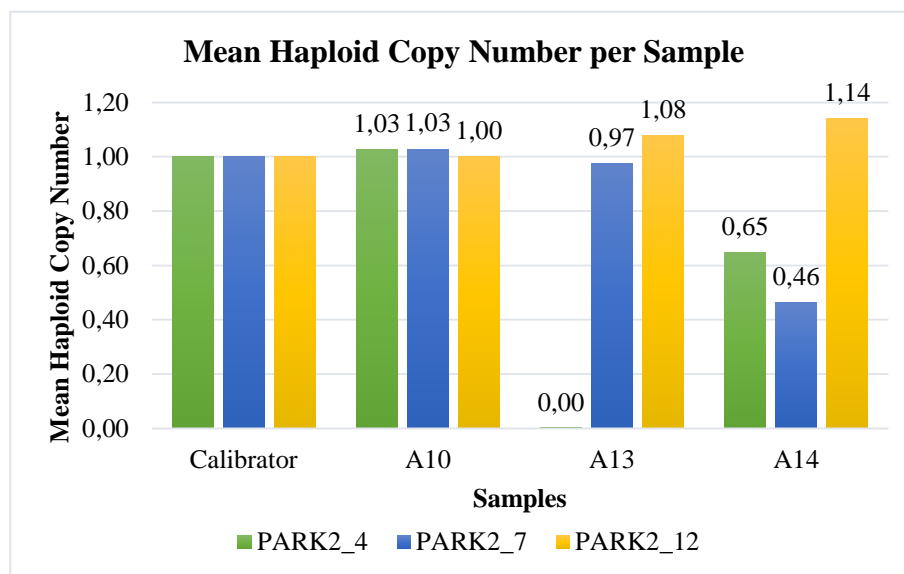


Figure 9 - Relative quantitation of the PARK2 gene, during method validation. Sample A10 had a normal haploid copy number (1.02 ± 0.01) for every primers pair. Sample A13 presented a normal copy number (1.03 ± 0.05) for exons 7 and 12, as well as a false homozygous deletion (0.00 ± 0.00) of exon 4. Sample A14 had a heterozygous deletion (0.55 ± 0.09) of exons 4 and 7, but it had a normal copy number for exon 12.

4) Results comparison

The qPCR results were compared to the previous results of aCGH, MLPA or other tests, in order to evaluate the sensitivity (false-negative results), specificity (false-positive results) and accuracy (true-value determination) of the qPCR approach. The total rate of concordant results was of 95%, the total rate of false-positive results was of 2,5%, and the rate of total false-negative results was of 2,5% (Figure 10).

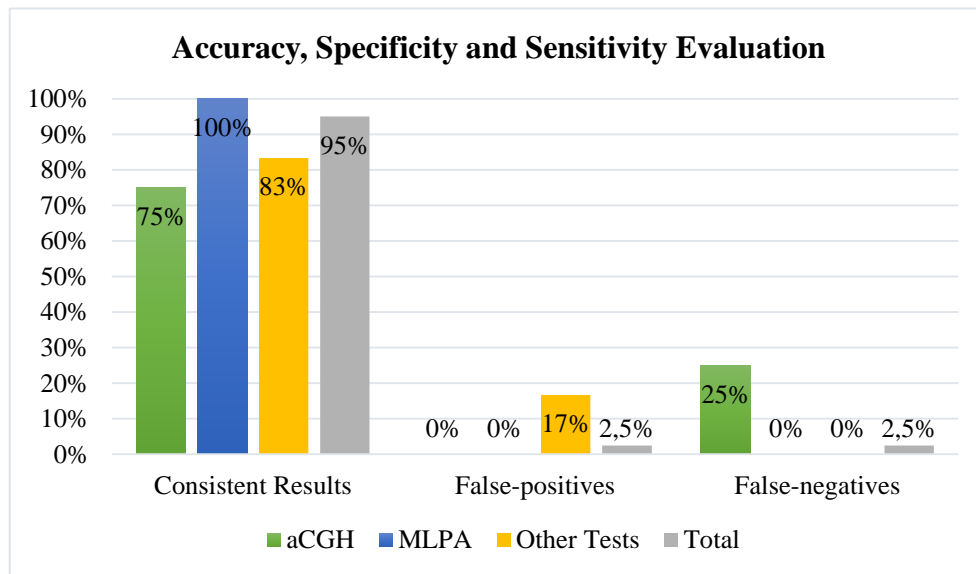


Figure 10 - Evaluation of the accuracy, specificity and sensitivity of the developed methodology.

qPCR and aCGH had 75% of their results in agreement, with the remaining 25% being false-negative aCGH results. MLPA and qPCR had all results consistent with each other. Other tests were 83% concordant with qPCR, however with a 17% rate of false positive results. Overall, qPCR had a total of 95% consistent results with other methods, as well as 2,5% of false-positives and 2,5% of false-negative results

Reference Genes

The relative quantitation method for CNVs detection requires the use of at least one reference gene for normalization³⁸. The *ZNF80* and *GPR15* genes were selected to be used as reference genes for the developed method, since they possess two copies in the human genome and deletions or duplications are not described in the Human Gene Mutation Database®. Both genes are located on the long arm of chromosome 3⁵². The zinc finger protein 80 (*ZNF80*) (MIM 194553) gene is located at the 3q13.31 locus, and the G protein-coupled receptor 15 (*GPR15*) (MIM 601166) gene is located at the 3q11.2 locus^{51,54,67,68}.

Both *ZNF80* and *GPR15* genes were validated at the melting temperatures of 95°C and 99° C, with a mean efficiency of 0,89(±0,07) and a R² of 0,9911 to 0,99708 (Figure 11). During the relative quantitation for CNVs detection, *ZNF80* was first used as the reference gene. When the mean haploid copy numbers calculated using the *ZNF80* gene were in close proximity with the cut-off values or between the cut-off values for deletion/normal or normal/duplication, the tested fragments were re-tested using the *GPR15* gene as reference gene. Both genes proved to be good candidate genes for normalization in the developed methodology.

Primers validation

In order to validate the designed primers, standard curves were retrieved for each primers pair, from qPCR assays of a dilution series of genomic DNA with normal copy number for the tested fragments. The efficiencies were considered acceptable when between 90% and 110%, however, efficiencies over 80% were accepted in several cases. The R², which indicates the reproducibility of the results, was accepted when superior to 0,98, even though it should be preferably over 0,99.

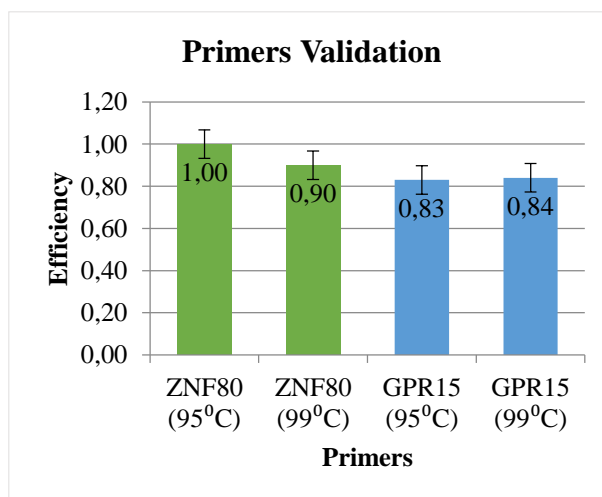


Figure 11 - Efficiency of the primers for the reference genes, using the cycling programs with melting temperatures of 95°C and 99°C.

The mean efficiency of the primers pairs was 0,89±0,07, with the primers pair the *GPR15* gene with lower efficiencies than the ones for *ZNF80*.

Nonetheless, in a few cases an inferior value had to be accepted.

A melt curve was performed to evaluate the specificity of the primers pairs. The primers pairs with a single sharp peak in the melt curve were considered acceptable, since they show the amplification of only one fragment, and do not form primer dimers. Also, primers pairs with a melting curve according to the prediction by uMelt were accepted, since small sequences with a high CG ou AT content might cause small deviations of the peak.

However, some primer pairs could not be validated since the efficiency was much higher than 110% or much lower than 80%, the R^2 were too low and/or the melting curves showed a non-specific fragment or failure of amplification (Table 1). In these cases, primers were redesigned in the proximities of the first sequence.

Table 1 - Efficiency, R^2 and PCR conditions of the not validated primers.

Primer	Efficiency	R^2	Primer Volume (μL)	Melting Temperature ($^{\circ}$C)
CC2D1A_26	1,80	0,905	0,4	95
COL6A1_12	2,66	0,781	0,4	99
COL6A1_12v2	2,48	0,724	0,4	99
COL6A1_35	0,36	0,890	0,4	95
COL6A2_6	8,56	0,755	0,4	99
COL6A2_29	2,20	0,943	0,2	95
COL6A3_44	0,60	0,947	0,4	95
SBF1_2	5,61	0,889	0,4	95
SLC5A2_3	1,50	0,986	0,2	95

In the end, 128 primer pairs were validated for the 33 genes that were assessed. The validated primers had a mean efficiency of $0,91 \pm 0,08$ and a mean R^2 of $0,99 \pm 0,01$ (Figure 12, Table S4).

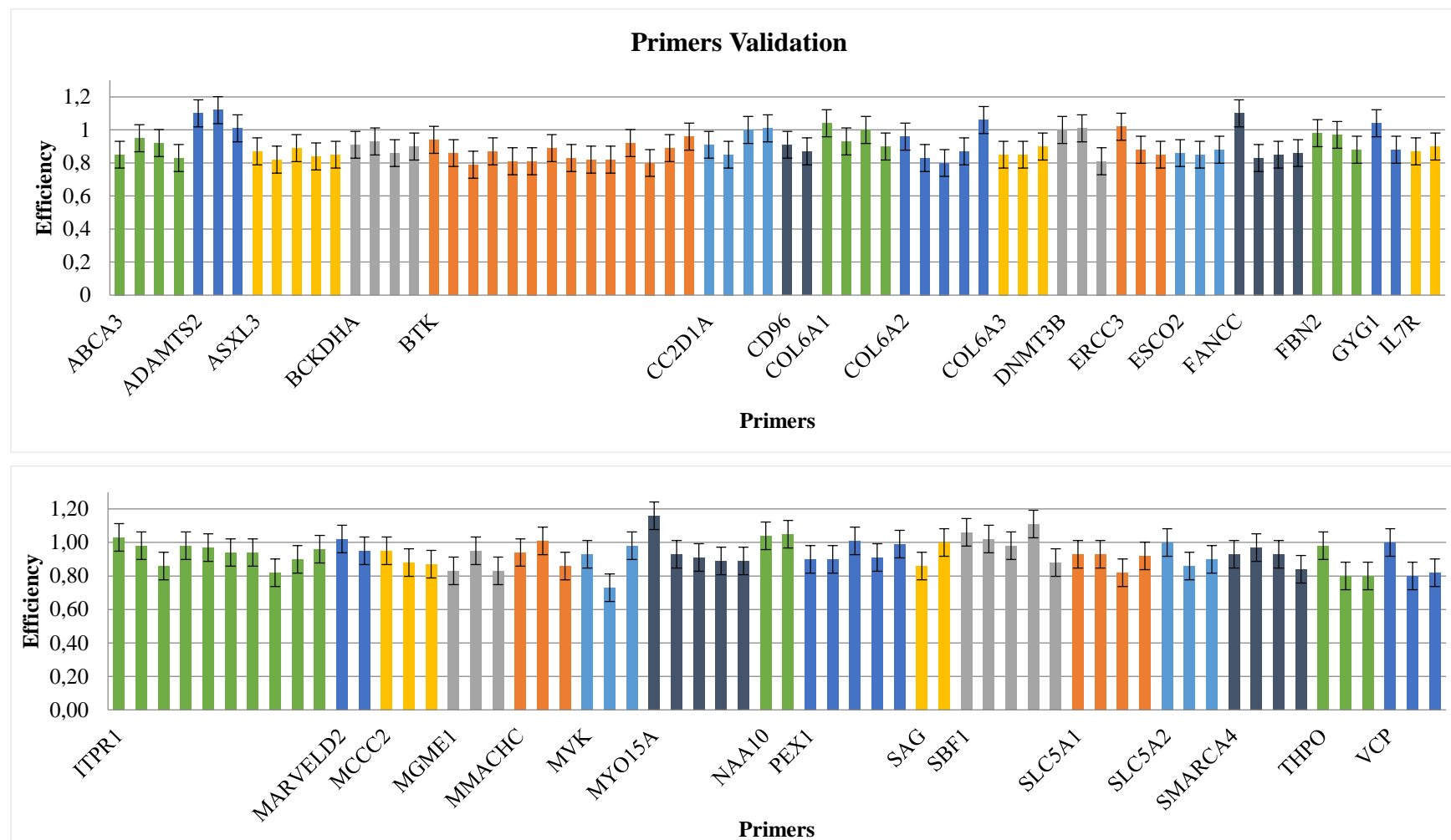


Figure 12 – Efficiencies of the primers pairs of the tested genes.

The mean efficiency of the primers pairs was $0,91 \pm 0,08$, for the 33 tested genes. Primers were validated with a DNA dilution series of samples with normal copy number for the tested fragments. The efficiencies were acceptable when higher than 0,80, although in some primers pairs an inferior value had to be accepted.

Scoring limits

For scoring a sample as having a deletion, a duplication or a normal copy number for the tested fragment, theoretical cut-off values were set. For the tested fragments, the cut-off values were set based on the values of previous studies, such as 0,7 for deletion upper limit⁵¹⁻⁵³, 0,8 for normal lower limit⁵¹⁻⁵³, 1,2 for normal upper limit⁵³ and 1,25 for duplication lower limit⁵⁰. At the time this methodology was initiated, no hemizygous duplication cut-off values were set theoretically. However, it was expected that the mean haploid copy number for a hemizygous duplication was approximately 2, since one copy would be represented as 1. Similarly, a homozygous deletion was expected to present a mean haploid copy number close to 0 (zero), since replication should not occur.

In the future, for the next tested fragments, the mean values of the haploid copy number of fragments previously scored as deleted, duplicated and normal was used for the calculation of the cut-off values (Table S5; Table S6; Table S7). The mean value of the haploid copy number in deleted fragments plus two times the standard deviation is set as the upper limit for scoring a deletion. For scoring a normal fragment, the mean value of the normal haploid copy number minus two times the standard deviation is set as the lower limit and the mean value of the normal haploid copy number plus two times the standard deviation is set as the higher limit. However, since at this time no heterozygous duplications other than the ones used in the methodology validation were detected, the lower limit for scoring a duplication could not be readjusted. The mean haploid copy numbers of the Pool F (female pool), scored as duplicated for the fragments from the X chromosome genes *BTK* and *NAA10* can be used to calculate the lower limit for a hemizygous duplication.

At the moment, it is set that the values are: 0,67 for heterozygous deletion upper limit; 0,85 for normal lower limit and 1,15 for normal upper limit; 1,25 for heterozygous duplication lower limit; 1,84 for hemizygous duplication lower limit and 2,33 for hemizygous duplication upper limit (Table 2).

Table 2 - Scoring limits for scoring a deletion, duplication or normal copy number sample, based on the mean haploid copy numbers and standard-deviation of the test and control samples.

Sample Type	Mean Haploid Copy Number	Standard-deviation	Lower Limit	Upper Limit
Normal	1,00	0,07	0,85	1,15
Heterozygous Deletion	0,53	0,07	0,38	0,67
Heterozygous Duplication	-	-	1,25	-
Hemizygous Duplication	2,08	0,12	1,84	2,33

Relative Quantitation for CNVs Detection

Data analysis of the qPCR results from RotorGene-Q was performed using the Microsoft Office Excel software and copy number alterations were calculated according to the Delta Delta Ct method ($2^{-\Delta\Delta C_t}$). This method allows the normalization of the test sample results through a normal copy number control (calibrator) and a housekeeping gene.

During the implementation of the methodology, the majority of the analysed samples had a normal copy number for the tested gene fragments. One homozygous deletion was detected for the *BCKDHA* gene and heterozygous deletions were found in the *COL6A1* and *ABCA3* genes. Moreover, two genes from the X chromosome, *BTK* and *NAA10*, were assessed. Significant results are presented in more detail below.

The comparison of the haploid copy number values for the deleted vs. control samples and duplicated vs. control samples, through the F test and two-sample *t-test*, allowed the determination of the statistical strength of the qPCR approach. The fragments analysed were considered statistically significant when $p\text{-value} < 0,05$ and confidently assessed as deleted or duplicated.

The results from the quantitative PCR showed that test fragments scored as normal, had a mean haploid copy number of $0,98 \pm 0,08$, fragments scored as deleted (in heterozygosis) had a haploid copy number of $0,53 \pm 0,07$ and fragments scored as duplicated (in hemizygosis) had a haploid copy number of $2,08 \pm 0,12$. Moreover, the negative control samples used had a mean haploid copy number of $1,01 \pm 0,06$.

1) *Heterozygous deletion in COL6A1 gene*

The *COL6A1*, *COL6A2* and *COL6A3* genes encode three of the collagen VI chains, which is an important component of the extracellular matrix^{69,70}. Mutations in each of the previous genes cause two main types of muscle disorders, being Ullrich congenital muscular dystrophy (UCMD) or Bethlem myopathy (BM)⁷⁰. Although not very frequent, large deletions (deletions of exons 9 to 10, 9 to 13 and 9 to 14 and deletion of the exon 12) have been described in the *COL6A1* gene, namely in association with Bethlem Myopathy⁷¹. Also, the *COL6A2* gene can present some large deletions (deletion of intron 1, exons 1 to 18, exon 5, exons 5 to 8, intron 5 to exon 7, exons 6 to 10, exons 9 to 28, exon 10, exon 11, exons 26 to 28, entire gene), mainly associated with UCMD⁷². Until present, no CNVs have been described for the *COL6A3* gene⁷³.

The patient analyzed by us had a clinical suspicious of Bethlem myopathy or Ulrich congenital muscular dystrophy. Previous molecular studies for *MYOT*, Pompe, *LMNA*, *CAV3* and *SEPI* were negative. Also, immunohistochemical analysis was negative for sarcoglycans and dysferline. Moreover, the NGS panel for congenital muscular dystrophies did not detect any mutations in the analysed genes. Therefore, a deletion/duplication search through qPCR was requested for the *COL6A1*, *COL6A2* and *COL6A3* genes.

A heterozygous deletion c.(1002+1_1003-1)_(1056+1_1057-1)del was detected in the *COL6A1* gene. The detected variant is a deletion in heterozygosis which encompasses at least exon 14 of the *COL6A1* gene. The result was first detected using the *ZNF80* gene as the reference gene (Figure 13 - a) and the sample was re-tested for fragment using the *GPR15* as reference gene (Figure 13 - b), which confirmed the deletion. This deletion is not described in the literature neither in databases of polymorphisms. Therefore, it was considered a variant of unknown clinical significance (VOUS) that could not confirm or exclude the clinical diagnosis of Bethlem myopathy. Nevertheless, the patient's father is also affected and has a similar clinical presentation; being so, a recommendation was made in order to study the father to assess if the deletion segregates with the phenotype.

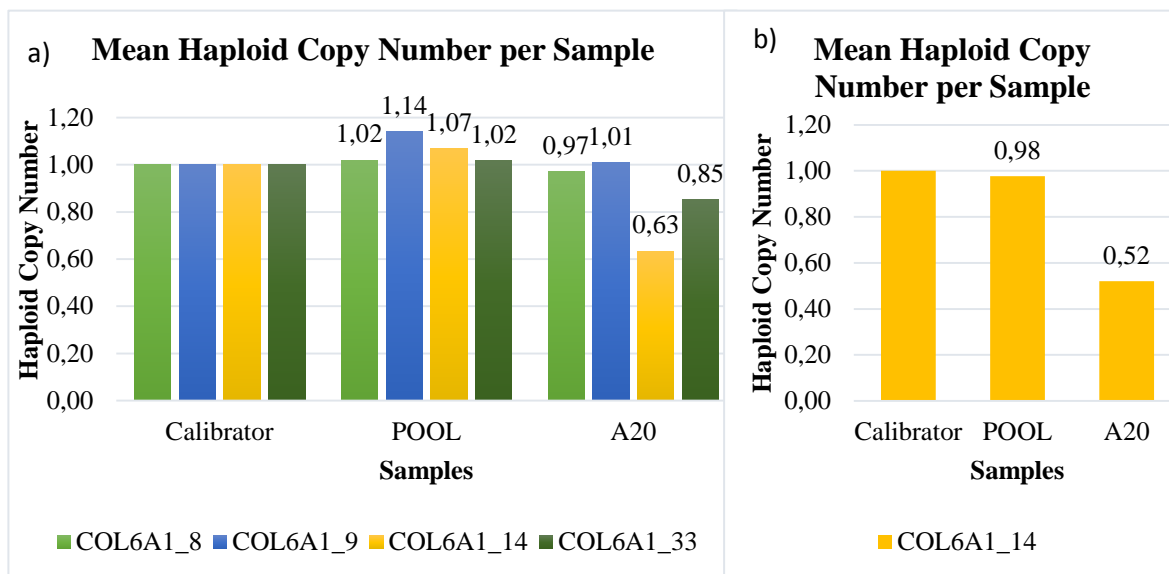


Figure 13 - Relative quantitation for the COL6A1 gene.

The pool of samples used as normal control showed a normal copy number ($1,04 \pm 0,06$). Sample A20 had a normal haploid copy number ($0,94 \pm 0,07$) for the primers pairs of exon 8, 9 and 33, as well as a heterozygous deletion of exon 14, using the ZNF80 as reference gene (left). The heterozygous deletion of exon 14 was confirmed using the GPR15 as reference gene (right).

No deletions or duplications were detected in the remaining genes studied, COL6A2 (Figure 14) and COL6A3 (Figure 15). Therefore, it was considered that these results did not allow us to attribute a genetic etiology to the patient clinical presentation.

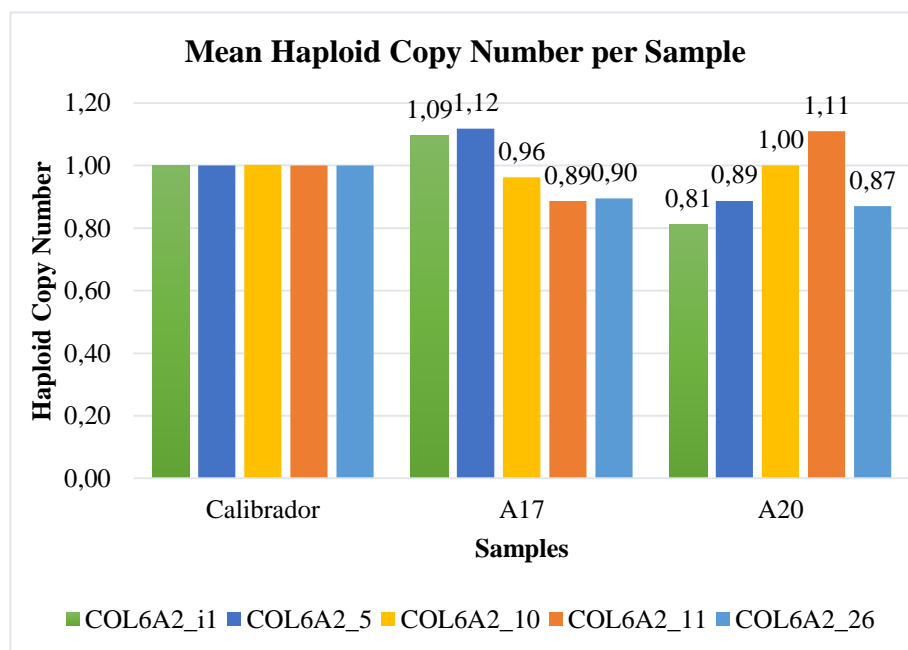


Figure 14 - Relative quantitation for the COL6A2 gene

Sample A17 used as normal control showed a normal copy number ($1,00 \pm 0,10$).

Sample A20 had a normal haploid copy number ($0,93 \pm 0,10$) for all primers pairs.

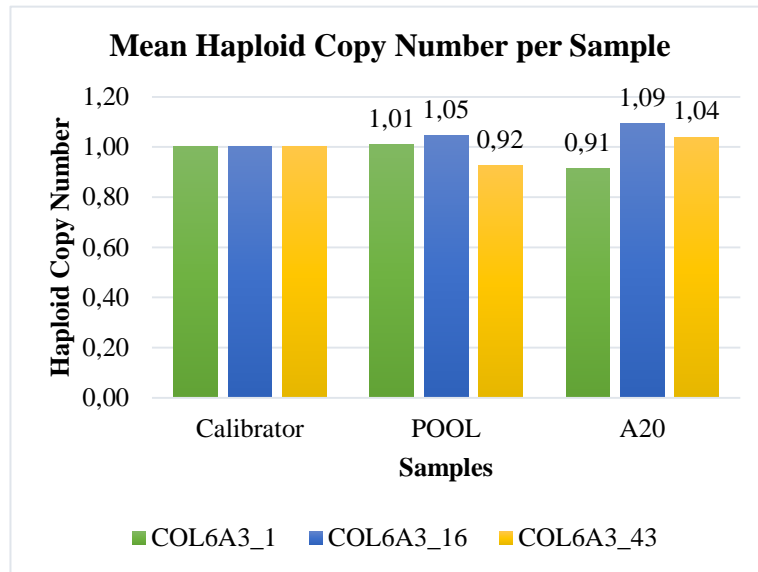


Figure 15 - Relative quantitation of the COL6A3 gene.
The pool of samples used as normal control showed a normal copy number (0.99 ± 0.05). Sample A20 had a normal haploid copy number (1.02 ± 0.08) for all primers pairs.

2) *Homozygous deletion in the BCKDHA gene*

The *BCKDHA* gene encodes the alpha subunit of the decarboxylase component of the branched-chain alpha-keto acid dehydrogenase (BCKD) complex. This complex catalyses the oxidative decarboxylation of the branched-chain α -ketoacids derived from the branched-chain amino acids leucine, isoleucine, and valine⁷⁴. Maple Syrup Urine Disease (MSUD) (MIM #248600) is a rare autosomal recessive disorder of metabolism caused by the defective function of the mitochondrial BCKD. When one of the four catalytic subunits, encoded by nuclear genes (*BCKDHA*, *BCKDHB*, *DBT* and *DLD*), is functionally impaired the complex's activity is reduced and the respective branched-chain α -ketoacids accumulate in body fluids to toxic levels⁷⁵. HGMD reports 4 gross deletions (deletion of exons 2 to 4, deletion of exon 4, deletion of exon 6 and deletion of exons 5 to 8) and one gross duplication (duplication of exons 2 to 4) of the *BCKDHA* gene, all related to MSUD⁷⁶.

The patient under study had a clinical suspicion of MSUD. First, Sanger sequencing of the *BCKDHB* and *BCKDHA* genes were performed, which did not detect any mutations in the analysed regions. However, no amplification of exons 2 and 3 of the *BCKDHA* gene could be obtained. Subsequently, CNVs detection through qPCR was requested, which confirmed a homozygous deletion c.(108+1_109-1)_(375+1_376-1)del in the *BCKDHA* gene (Figure 16). This mutation is a novel deletion, not described in the literature, which includes at least exons 2 to 3 of the *BCKDHA* gene. Nonetheless, a similar deletion has been described in patients with maple syrup urine disease⁷⁷.

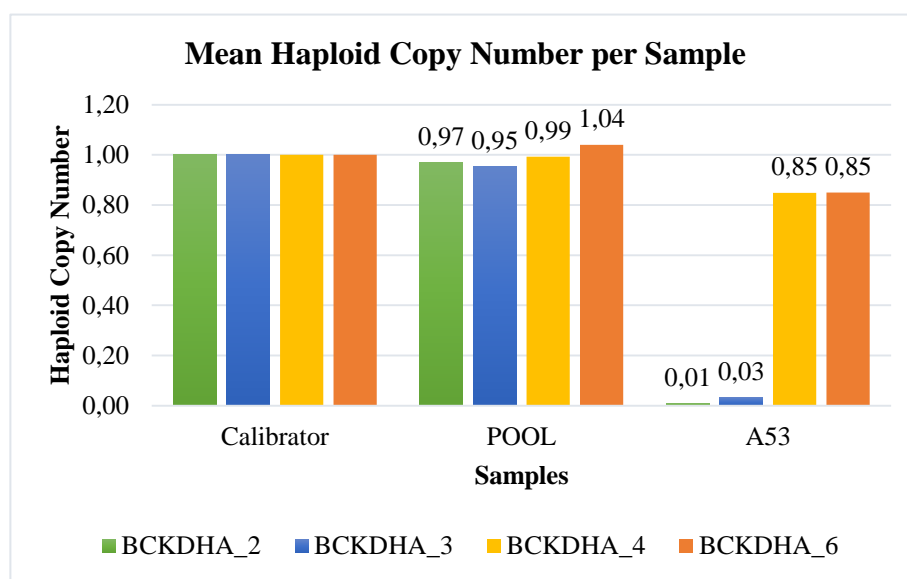


Figure 16 - Relative quantitation for the *BCKDHA* gene.

The pool of samples used as normal control showed a normal copy number (0.99 ± 0.03). Sample A53 had a normal haploid copy number (0.85 ± 0.00) for primers pairs of exons 4 and 6, as well as a false homozygous deletion (0.02 ± 0.01) of exons 2 and 3.

3) Heterozygous deletion in the *ABCA3* gene

The ATP-binding cassette A3 (*ABCA3*) gene is an 80kB gene mapped to human chromosome 16p13.3⁷⁸. It encodes a 1704-amino-acid protein highly expressed in the lung, which has been localized to the limiting membrane of lamellar bodies, implicating *ABCA3* as possibly important in the maturation of lamellar bodies and surfactant production⁷⁹. The concept that *ABCA3* mutations disrupt surfactant homeostasis is supported by clinical and pathologic findings in patients with *ABCA3* mutations, which present respiratory distress after birth associated with abnormally small lamellar body inclusions⁷⁸. Bi-allelic

mutations of *ABCA3* are the most frequent cause of surfactant metabolism dysfunction, pulmonary type 3 (MIM#610921)⁸⁰. HGMD reports 2 gross deletions (deletion of exons 2 to 5 and deletion of exon 12) of the *ABCA3* gene, related to Lung disease and Fatal surfactant deficiency⁸¹.

The patient had a clinical suspicion of pulmonary surfactant metabolism dysfunction, and a Surfactant Metabolism Dysfunction Panel (NGS panel) was requested. This panel detected the variant c.4442C>T (p.Ala1481Val), in apparent homozygosis, in the *ABCA3* gene. However, no mutations were detected in the remaining genes analysed in this panel. The detected variant is not described in the literature, being located in a highly conserved residue and bioinformatic analysis suggests that it is probably a pathogenic variant. Therefore, it was considered a VOUS. Also, the study of the parents revealed that this variant is of paternal origin.

Subsequently, a CNVs analysis through qPCR was performed. A heterozygous deletion c.(?_4910-1)_(4983+1_?)del was detected in the *ABCA3* gene. The detected variant is a deletion in heterozygosis which encompasses at least exon 32 of the *ABCA3* gene and most likely will include exon 29, where the variant was detected. The result was first detected using the *ZNF80* gene as the reference gene (Figure 17 - a) and the sample was re-tested for fragment using the *GPR15* as reference gene (Figure 17 - b), which confirmed the deletion. This deletion is not described in the literature neither in databases of polymorphisms. Therefore, it was considered a VOUS.

The qPCR result, together with the previous NGS panel result, might support the clinical diagnosis of pulmonary surfactant metabolism dysfunction type 3. Also, the apparent homozygous variant c.4442C>T (p.Ala1481Val) detected in the NGS panel corresponds, in fact, to a compound heterozygosity. Nevertheless, the study of the mother to confirm if she carries the detected deletion was recommended, as well as an additional qPCR to delimit the extent of the detected deletion.

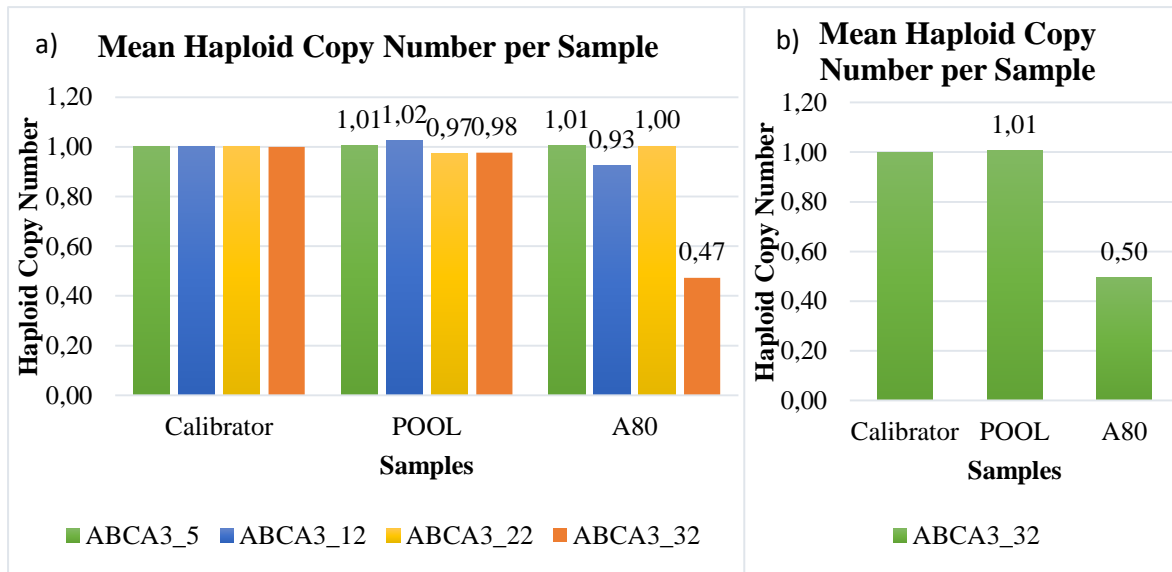


Figure 17 - Relative quantitation for the ABCA3 gene.

The pool of samples used as normal control showed a normal copy number ($1,00 \pm 0,02$). Sample A80 had a normal haploid copy number ($0,98 \pm 0,04$) for the primers pairs of exon 5, 12 and 22, as well as a heterozygous deletion of exon 32, using the ZNF80 as reference gene (left). The heterozygous deletion of exon 32 was confirmed using the GPR15 as reference gene (right).

4) CNVs search in genes from the X chromosome

The Bruton's tyrosine kinase (*BTK*) gene is localized on Xq21.3–Xq22, being a member of the Tec family of kinases⁸². X-linked agammaglobulinemia (XLA; MIM #300300) is a primary immunodeficiency caused by deleterious variations in *BTK*. XLA presents a drastic decrease in the number of B lymphocytes, a severe reduction of all immunoglobulin isotypes and recurrent bacterial and enteroviral infections. Therefore, the defect blocks B-lymphocyte development between the pro- and pre-B-cell stage⁸³. HGMD reports several gross deletions and duplications of the *BTK* gene, mostly related to XLA, with a few related to *BTK* deficiency or Mohr-Tranebjaerg syndrome. Furthermore, the described deletions and duplications encompass almost every single exon of the gene⁸⁴.

The patient studied was a male with a clinical suspicion of XLA, for which it was requested both sequencing and deletion/duplication analysis of *BTK* gene. Sanger sequencing of the *BTK* gene was performed, which detected a hemizygous c.82C>T (p.Arg28Cys) variant, described in the literature and already reported in other patients and families with XLA⁸⁵, confirming the clinical diagnosis of X-linked agammaglobulinemia type 1 caused by mutation in the *BTK* gene. On the other hand, CNVs detection through qPCR did not detect any deletions or duplications in the analysed regions (Figure 18).

Since it was a gene from the X chromosome and the test sample was male, the pools of samples used as calibrators, as well as the pool of samples used as normal control, only contained male samples. As expected, the later showed a normal copy number, so did the test sample, for all pairs of primers. Nevertheless, the positive control (pool of female samples) had a copy number of $2,05 \pm 0,17$, accordingly with the predicted results, because female samples possess two X chromosomes, therefore the double of the *BTK* sequence. However, exon 19 showed normal copy number for the normal control and test samples, but a slightly lower relative quantitation for the female pool. This might be explained by germline mosaicism of at least one of the samples from the pool, or a side effect of the X-chromosome inactivation^{86,87}.

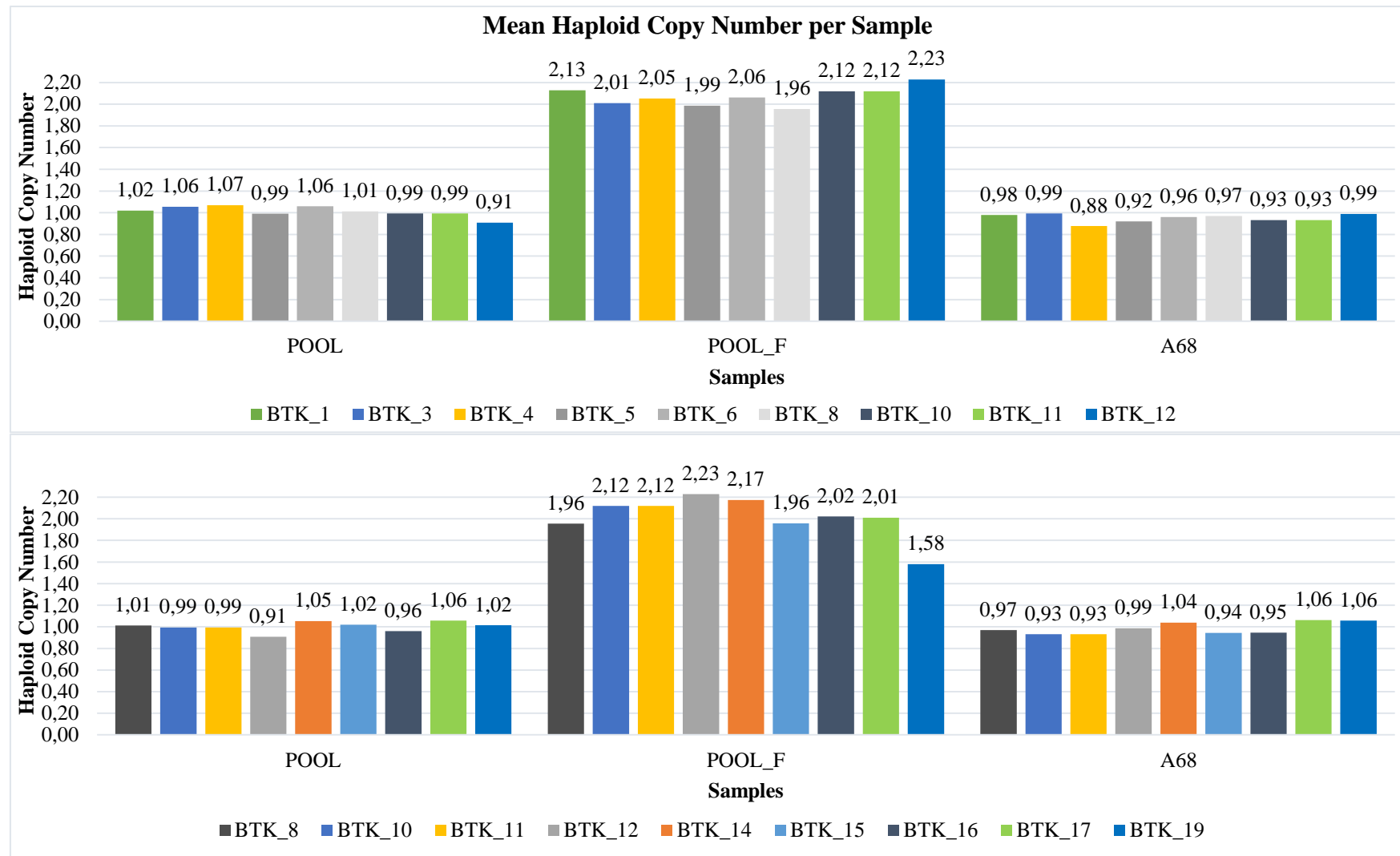


Figure 18 - Relative quantitation of the BTK gene.

The pool of samples used as normal control showed a normal copy number ($1,01 \pm 0,04$), while POOL_F had a copy number of $2,05 \pm 0,17$, confirming the duplication of the gene sequence. Sample A68 had a normal haploid copy number ($0,97 \pm 0,05$) for all primers pairs.

The *NAA10* gene is localized at Xq28, and codes for the catalytic subunit of the hNaTA complex⁸⁸. Pathogenic *NAA10* mutations are related to Lenz microphthalmia syndrome (LMS, MIM 309800), intellectual disability, arrhythmia and developmental delays⁸⁹. LMS is an X-linked, genetically heterogeneous disorder, characterized by unilateral or bilateral microphthalmia or anophthalmia and defects in the skeletal and genitourinary systems⁸⁸. HGMD does not have any described deletions or duplications of the *NAA10* gene⁹⁰.

The patient studied was a male with a clinical diagnosis of Lenz microphthalmia, with multiple studies, including a whole exome sequencing (WES), performed in another laboratory, with normal results. Therefore, deletion/duplication analysis of *NAA10* gene was requested, which did not detect any deletions or duplications in the analysed regions (Figure 19). This result could not confirm the clinical diagnosis of syndromic type 1 (or Lenz) microphthalmia caused by deletions/duplications in the analysed regions of the *NAA10* gene.

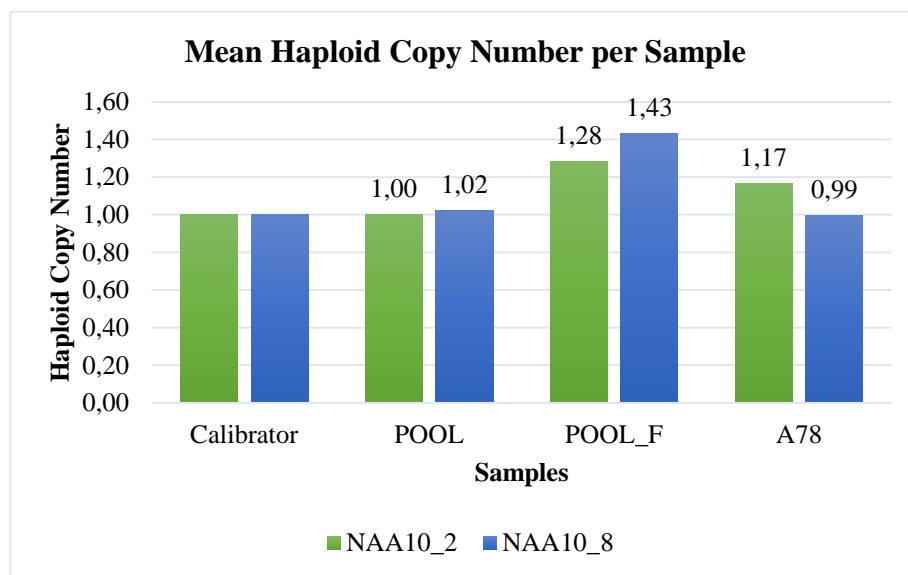


Figure 19 - Relative quantitation of the *NAA10* gene.

The pool of samples used as normal control showed a normal copy number (1.01 ± 0.01), while POOL_F had a copy number of 1.36 ± 0.08 . Sample A78 had a normal haploid copy number (1.08 ± 0.09) for all primers pairs.

In the same manner as the *BTK* gene, *NAA10* is a gene from the X chromosome with a male test sample. Therefore, the calibrators and normal control pools only contained male samples. The normal control and the test sample showed a normal copy number.

Again, the positive control had a mean haploid copy number slightly lower than expected, which also might be explained by germline mosaicism or a side effect of the X-chromosome inactivation^{86,87}.

Conclusion

This work allowed the development and validation of a methodology for CNVs detection in clinical diagnostics, through qPCR, using the relative quantitation method. The developed and optimized methodology proved to be accurate and specific, allowing the detection of autosomal homozygous and heterozygous deletions, heterozygous duplications, as well as deletions and duplications on fragments from the X chromosome.

However, this methodology cannot differentiate compound heterozygous deletions from homozygous deletions. Also, it is sensitive to SNPs which may impair the primers annealing and subsequent PCR, as well as cause allele dropout. Pseudogenes or other highly homologous sequences might interfere with the technical ability of variant identification in this analysis. Moreover, secondary structures and sequences very rich in CGs might interfere with the efficiency of PCR.

Therefore, the qPCR methodology requires a well-thought planning, from selection of regions and primers design up to data analysis. The presented method is easily adaptable for the screening of CNVs in several genetic diseases. So, this approach may be implemented as the method of choice in routine DNA diagnosis for deletion/duplication analysis in genes for which there is no MLPA kit, as well as to confirm CNVs in a particular gene, previously detected by another method (MLPA, aCGH, etc.).

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ANNEX I – Samples

Table S1 - Samples identification, matrix of extraction, CNV status and studied genes for the validation and development of the methodology.

Sample	Matrix	CNV Status	Studied Gene	Observations
A1	DNA	Normal	<i>MECP2</i>	
A2	Blood (EDTA)	Normal	<i>MECP2</i>	
A3	Blood (EDTA)	Normal	<i>MECP2</i>	
A4	Blood (EDTA)	Deleted	<i>MECP2</i>	
A5	Blood (EDTA)	Duplicated	<i>MECP2</i>	
A6	Blood (EDTA)	Normal	<i>PARK2; FANCC; COL6A2; VCP; DNMT3B; SBF1</i>	Del SMN1
A7	Blood (EDTA)	Normal	<i>NF1; FANCC; COL6A1; CC2D1A; COL6A2; BCKDHA; SLC5A1; MMACHC; CD96; ASXL3; MYO15A; SLC5A2</i>	Del SMN1
A8	Blood (EDTA)	Normal	<i>NF1; PARK2; FANCC; COL6A2; MYO15A; SLC5A2; CC2D1A; SBF1</i>	Del SMN1
A9	Blood (EDTA)	Normal	<i>NF1; PARK2; FANCC; RBM8A; SLC5A1</i>	Del SMN1
A10	Blood (EDTA)	Normal	<i>NF1; PARK2; FANCC; VCP; DNMT3B</i>	Del DMD
A11	Blood	Deleted	<i>NF1</i>	
A12	Blood (EDTA)	Test	<i>NF1</i>	
A13	Blood (EDTA)	Deleted	<i>PARK2</i>	
A14	Blood (EDTA)	Test	<i>PARK2</i>	
A15	Blood (EDTA)	Normal	<i>COL6A1; COL6A3; COL6A2; MYO15A; ESCO2; ASXL3</i>	Del SMN1
A16	DNA	Test	<i>FANCC</i>	
A17	Blood (EDTA)	Normal	<i>FANCC; COL6A2; THPO</i>	Del DMD
A18	Blood (EDTA)	Normal	<i>FANCC; COL6A2; CC2D1A; SLC5A2; SBF1; PEX1</i>	Del NF1
A19	Blood (EDTA)	Normal	<i>FANCC; COL6A2; THPO; ESCO2</i>	Del DMD
A20	Blood (EDTA)	Test	<i>COL6A1; COL6A2; COL6A3</i>	
A21	Blood (EDTA)	Normal	<i>IL7R; MVK; COL6A2; THPO; MGME1</i>	Del DMD
A22	Blood (EDTA)	Normal	<i>MVK; THPO; MGME1; PEX1; COL6A1; COL6A3</i>	Del DMD

(cont.) Table S1 - Samples identification, matrix of extraction, CNV status and studied genes for the validation and development of the methodology.

Sample	Matrix	CNV Status	Studied Gene	Observations
A23	N/A	Normal	<i>COL6A2; THPO; COL6A3; IL7R; MGME1; ESCO2; MYO15A; ASXL3</i>	CT_NGS
A24	N/A	Normal	<i>COL6A2; THPO; COL6A3; IL7R; MGME1; ESCO2; MYO15A; ASXL3</i>	CT_aCGH
A25	DNA	Test	<i>THPO</i>	
A26	Blood (EDTA)	Normal	<i>COL6A3; IL7R; MGME1; ESCO2; MYO15A</i>	POOL_M_MLPA
A27	Blood (EDTA)	Normal	<i>COL6A3; IL7R; MGME1; ESCO2; MYO15A</i>	POOL_M_MLPA
A28	Blood (EDTA)	Normal	<i>COL6A3; IL7R; MGME1; ESCO2; MYO15A</i>	POOL_M_MLPA
A29	Blood (EDTA)	Normal	<i>COL6A3; IL7R; MGME1; ESCO2; MYO15A</i>	POOL_F_MLPA
A30	Blood (EDTA)	Normal	<i>COL6A3; IL7R; MGME1; ESCO2; MYO15A</i>	POOL_F_MLPA
A31	Blood (EDTA)	Normal	<i>COL6A3; IL7R; MGME1; ESCO2; MYO15A</i>	POOL_F_MLPA
A32	Blood (EDTA)	Test	<i>IL7R</i>	
A33	Blood (EDTA)	Test	<i>MGME1</i>	
A34	DNA	Test	<i>ESCO2</i>	
A35	Blood (EDTA)	Test	<i>MYO15A</i>	
A36	Blood (EDTA)	Normal	<i>ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; NAA10; ESCO2</i>	POOL_M
A37	Blood (EDTA)	Normal	<i>ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; NAA10; ESCO2</i>	POOL_M
A38	Blood (EDTA)	Normal	<i>ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; NAA10; ESCO2</i>	POOL_M

(cont.) Table S1 - Samples identification, matrix of extraction, CNV status and studied genes for the validation and development of the methodology.

Sample	Matrix	CNV Status	Studied Gene	Observations
A39	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; NAA10; ESCO2	POOL_F
A40	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; NAA10; ESCO2	POOL_F
A41	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; NAA10; ESCO2	POOL_F
A42	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; BTK; MARVELD2; GYG1; SMARCA4; ESCO2	POOL_3
A43	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; MARVELD2; GYG1; SMARCA4; ESCO2	POOL_3
A44	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; MARVELD2; GYG1; SMARCA4; ESCO2	POOL_3

(cont.) Table S1 - Samples identification, matrix of extraction, CNV status and studied genes for the validation and development of the methodology.

Sample	Matrix	CNV Status	Studied Gene	Observations
A45	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; MARVELD2; GYG1; SMARCA4; ESCO2	POOL_4
A46	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; MARVELD2; GYG1; SMARCA4; ESCO2	POOL_4
A47	Blood (EDTA)	Normal	ASXL3; PEX1; MVK; FANCC; COL6A1; SLC5A1; BCKDHA; MYO15A; COL6A2; MMACHC; SAG; ADAMTS2; CC2D1A; ERCC3; FBN2; SLC5A2; VCP; CD96; SBF1; ITPR1; DNMT3B; IL7R; THPO; MARVELD2; GYG1; SMARCA4; ESCO2	POOL_4
A48	Blood (EDTA)	Test	ASXL3	
A49	Blood (EDTA)	Test	ASXL3	
A50	DNA	Test	PEX1; MVK	
A51	Blood (EDTA)	Normal	FBN2; MMACHC; ASXL3; BCKDHA; ADAMTS2; SAG; COL6A2; SLC5A2; COL6A1; ERCC3; FANCC	
A52	DNA	Test	SLC5A1	
A53	Blood (EDTA)	Test	BCKDHA	
A54	Blood (EDTA)	Test	MMACHC	
A55	Blood (EDTA)	Test	SAG	
A56	Blood (EDTA)	Test	ADAMTS2	
A57	Blood (EDTA)	Test	CC2D1A	
A58	Blood (EDTA)	Test	ERCC3	
A59	Blood (EDTA)	Test	FBN2	
A60	Blood (EDTA)	Test	SLC5A2	

(cont.) Table S1 - Samples identification, matrix of extraction, CNV status and studied genes for the validation and development of the methodology.

Sample	Matrix	CNV Status	Studied Gene	Observations
A61	Blood (EDTA)	Test	<i>VCP</i>	
A62	Blood (EDTA)	Test	<i>CD96</i>	
A63	Blood (EDTA)	Test	<i>SBF1</i>	
A64	Blood (EDTA)	Test	<i>ITPR1</i>	
A65	Blood (EDTA)	Test	<i>DNMT3B</i>	
A66	Blood (EDTA)	Test	<i>IL7R</i>	
A67	DNA	Test	<i>THPO</i>	
A68	DNA	Test	<i>BTK</i>	
A69	Blood (EDTA)	Normal	<i>BTK; NAA10</i>	POOL_M1_MLPA
A70	Blood (EDTA)	Normal	<i>BTK; NAA10</i>	POOL_M1_MLPA
A71	Blood (EDTA)	Normal	<i>BTK; NAA10</i>	POOL_M1_MLPA
A72	Blood (EDTA)	Normal	<i>BTK; NAA10</i>	POOL_M2_MLPA
A73	Blood (EDTA)	Normal	<i>BTK; NAA10</i>	POOL_M2_MLPA
A74	Blood (EDTA)	Normal	<i>BTK; NAA10</i>	POOL_M2_MLPA
A75	Blood (EDTA)	Test	<i>MARVELD2</i>	
A76	DNA	Test	<i>GYG1</i>	
A77	Blood (EDTA)	Test	<i>SMARCA4</i>	
A78	Blood (EDTA)	Test	<i>NAA10</i>	
A79	Blood (EDTA)	Test	<i>MCCC2</i>	
A80	Blood (EDTA)	Test	<i>ABCA3</i>	

ANNEX II -Primers

Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
ZNF80_1-F	GTGGCAGTAGGAAAGCTGTG	20	58,5	133	NM_007136.3
ZNF80_1-R	AGTTCTCTGACGTTGACTGATG	22	57,0	133	NM_007136.3
MECP2_2-F	CCCAGAATACACCTTGCTTCT	22	58,3	119	NM_004992
MECP2_2-R	GGCCAAACCAGGACATATACTA	22	58,0	119	NM_004992
MECP2_3-F	GGTCCAAGCCTGCCTCTG	18	62,0	186	NM_004992
MECP2_3-R	CTCATGCTTGCCCTCTTTC	19	58,5	186	NM_004992
MECP2_4A-F	CATCCGCTCTGCCCTATCT	19	60,3	150	NM_004992
MECP2_4A-R	AGGGATGTGTCGCCTACCT	19	59,5	150	NM_004992
MECP2_4B-F	GAGAAGAGCGGGAAAGGAC	19	59,0	118	NM_004992
MECP2_4B-R	GGTGGTGGTGCTCCTTCT	18	58,6	118	NM_004992
MECP2_4C-F	ACATTGTTTCATCCTCCATGC	21	59,8	164	NM_004992
MECP2_4C-R	TCAGAGCCCTACCCATAAGG	20	59,1	164	NM_004992
PARK2_4-F	TTCTCCAGCAGGTAGATCAATC	22	58,4	152	NM_004562.2
PARK2_4-R	TGCTGACACTGCATTTTCCTT	20	59,4	152	NM_004562.2
PARK2_7-Fv2	CCTCCAGGATTACAGAAATTGG	22	59,8	115	NM_004562.2
PARK2_7-Rv2	TGCACTGGAAAACCAGGA	18	58,7	115	NM_004562.2
PARK2_12-F	GCTCAGAAAGTGATGTCTAGGC	22	58,2	163	NM_004562.2
PARK2_12-R	ACAGTTCCAGCACCCTCG	19	59,9	163	NM_004562.2
NF1_13-F	ACAGACCTGGAGACAAGAAGC	21	58,5	151	NM_000267.3
NF1_13-R	GGCGTTTCAGCTAAACCC	18	58,3	151	NM_000267.3
NF1_14-F	CCTTGCAGAATCCAAGAAAAC	21	58,8	148	NM_000267.3
NF1_14-R	GAACATGGAATTCATTTTCCC	21	58,2	148	NM_000267.3
NF1_58-F	CGACACATGACTGCAATGAA	20	59,2	173	NM_000267.3
NF1_58-R	CTTCTTTGCTTCTGCACTTGG	21	60,2	173	NM_000267.3

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
FANCC_1-F	CCAGAATGCACTGCTGACAC	20	60,5	106	NM_000136.2
FANCC_1-R	AATTTGGCTTTGCCTCGTATT	21	60,0	106	NM_000136.2
FANCC_2-F	CACTTTGGAAACCCAGCAA	19	59,7	166	NM_000136.2
FANCC_2-R	GTGGCATTCTGTCTTGGTGA	20	59,7	166	NM_000136.2
FANCC_4-F	CCTTTTTGTAGATGAAAGCCAA	22	58,4	140	NM_000136.2
FANCC_4-R	TCAAAGAAGTGCAGAGCAAGA	21	58,9	140	NM_000136.2
FANCC_15-F	GTCCCTGGACAAAGGACAAA	20	59,9	120	NM_000136.2
FANCC_15-R	CTGGTCAAGAAAGCCAATGA	20	58,8	120	NM_000136.2
COL6A2_i1-F	GCCGCTGCCATCAGTAAT	18	59,8	173	NM_001849.3
COL6A2_i1-R	CAAGGACAAGCACTTCATGC	20	59,4	173	NM_001849.3
COL6A2_5-F	ACCCATGCAACCTTCTGTC	19	58,5	123	NM_001849.3
COL6A2_5-R	AGGTAATCTGGGCATCTTACCT	22	58,2	123	NM_001849.3
COL6A2_7-F	GCTCACACTGCTGCGTTGT	19	61,3	199	NM_001849.3
COL6A2_7-R	TGCTTCTGTTCTTGGTAACTG	22	59,4	199	NM_001849.3
COL6A2_10-F	TTCCTTCTCTCTTCAGGGGG	20	60,7	113	NM_001849.3
COL6A2_10-R	CTGGGATGCCTCTGTGAGAC	20	60,8	113	NM_001849.3
COL6A2_11-F	GGCTGTGTCTTGGTCGTTG	19	60,3	127	NM_001849.3
COL6A2_11-R	GTTTCCAGGGTCTCCCTTG	19	59,5	127	NM_001849.3
COL6A2_29-F	GAATGGAAGGGCACAGGTG	19	61,5	101	NM_001849.3
COL6A2_29-R	TGCCACGGACAGCTCTGT	18	61,7	101	NM_001849.3
COL6A1_8-F	AACCTGAGTCTGGGGTCCT	19	58,5	108	NM_001848.2
COL6A1_8-R	GCAGGAGTCACCACTCACC	19	59,2	108	NM_001848.2
COL6A1_9-F	CCCAACCTTGACCTGTTTTG	20	60,4	185	NM_001848.2
COL6A1_9-R	ACTTTGGCACTCAGAACCCA	20	60,7	185	NM_001848.2
COL6A1_12-F	CACTGTCAGTCCCCATGATTC	21	60,4	178	NM_001848.2
COL6A1_12-R	CTCACCTTGTAGCCCTTGGG	20	61,9	178	NM_001848.2

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
COL6A1_35-F	CAGACAGTCTCCAGGAAGGTG	21	59,9	119	NM_001848.2
COL6A1_35-R	GGAAAATTCGCATCACATTTT	21	58,9	119	NM_001848.2
COL6A3_1-F	ACGCAGTGAGTGGGAAAAGT	20	59,8	124	NM_004369.3
COL6A3_1-R	CCCAAACCTGGAAAAACAGA	20	59,9	124	NM_004369.3
COL6A3_16-F	GTGCTGCTCTGCCAAATG	18	59,1	113	NM_004369.3
COL6A3_16-R	CTTCTCCAGGAATACCCTGAA	21	58,3	113	NM_004369.3
COL6A3_44-F	GTGCCCTTTTGGGTCAGTAA	20	60,0	177	NM_004369.3
COL6A3_44-R	ATGGCTGACTCCTTCTTCTTCA	22	60,4	177	NM_004369.3
IL7R_3-F	GAACATGCCTCCACTCACC	19	59,0	154	NM_002185.3
IL7R_3-R	GCCCCACTGTAGGAATAAAAAG	22	59,1	154	NM_002185.3
IL7R_8-F	CCTGACATTGAACCCAGTTG	20	59,0	191	NM_002185.3
IL7R_8-R	GCTGTGAGGGAGACTAGGAACT	22	59,0	191	NM_002185.3
THPO_3-F	AACTGCAAGGCTAACGCTGT	20	60,1	123	NM_000460.3
THPO_3-R	GGGATAATGTTGGGAGTTCTCA	22	60,2	123	NM_000460.3
THPO_4-F	CAGAGGTCACCCCTTGCCTA	21	61,5	101	NM_000460.3
THPO_4-R	CAAGGTTAGGGATGGCTTTCTT	22	60,8	101	NM_000460.3
THPO_6-F	CCCCTACCAGCCCTCTTCTA	20	60,6	179	NM_000460.3
THPO_6-R	GGCTTTGGGTTTCAGGAGA	19	60,2	179	NM_000460.3
MGME1_2-F	ACAGCGGATGATTCTGGAAC	20	60,1	126	NM_052865.3
MGME1_2-R	CATTCTTTTGACACCGTTGC	20	59,2	126	NM_052865.3
MGME1_3-F	AAGTGCTGTTCAACATGAAACC	22	59,1	174	NM_052865.3
MGME1_3-R	GCACAAAGGTCTGGACATTAAG	22	59,1	174	NM_052865.3
MGME1_5-F	TGCCCTGGAGTAAGAAGGAA	20	59,8	186	NM_052865.3
MGME1_5-R	GAAGAAGCCACTTGGTCCAG	20	59,8	186	NM_052865.3
PEX1_6-F	TCAGGATAACTCCAGTGGAAGTT	23	59,2	140	NM_000466.2
PEX1_6-R	GCTAAAGCAACTAGAAATCTTACAAA	27	58,1	140	NM_000466.2

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
PEX1_9-F	GCAACTGTAGGTCCTTAGATCC	24	59,7	165	NM_000466.2
PEX1_9-R	TTACATTGAAAACCTCTGCCAGAT	23	58,0	165	NM_000466.2
PEX1_12-F	GTGCTTTCAAAAGGACAACCTG	22	61,0	149	NM_000466.2
PEX1_12-R	ACAGATGGCTGCATCCACA	19	61,3	149	NM_000466.2
PEX1_14-F	TTTACTTAAGGAGGACGAATCCA	23	59,2	123	NM_000466.2
PEX1_14-R	CAGTCATCTTCACTAATGGATGG	23	58,6	123	NM_000466.2
PEX1_24-F	GCTTTCAAAATCCAAAGAGGA	21	58,4	139	NM_000466.2
PEX1_24-R	GTTACAACATATGGAAAAGCCATC	24	58,9	139	NM_000466.2
MVK_3-F	CAATGGGAAAGTGGACCTCA	20	60,9	144	NM_000431.3
MVK_3-R	CTGCCCTCTCTGTAGGCTCTT	21	60,2	144	NM_000431.3
MVK_4-F	CATCCATGTTCCAATTCCAGT	21	59,7	113	NM_000431.3
MVK_4-R	TTGCTCTGTTCCACAGGCA	19	61,6	113	NM_000431.3
MVK_6-F	CAGGTGGACCAAGGAGGA	18	59,6	188	NM_000431.3
MVK_6-R	AGCACAGACTCTTGGGCA	18	58,0	188	NM_000431.3
MYO15A_2-F	AAGCTGGCGGAACAAGGTAT	20	61,0	121	NM_016239.3
MYO15A_2-R	AAGCAGCCTCTCTCCAAGGT	20	60,5	121	NM_016239.3
MYO15A_16-F	CAGGACCTGAGCTTCAACAG	20	58,6	101	NM_016239.3
MYO15A_16-R	ACCTGCTCCTCCTGGAAGA	19	59,9	101	NM_016239.3
MYO15A_30-F	CACAATGCCCACAATGCT	18	59,0	107	NM_016239.3
MYO15A_30-R	AGTCCCACTCACTTGAGAAGG	21	58,4	107	NM_016239.3
MYO15A_45-F	CCTGCATCACAGCCTGTTC	19	60,4	152	NM_016239.3
MYO15A_45-R	TGTGCCTCTGACTGGTTGC	19	61,1	152	NM_016239.3
MYO15A_66-F	CTCCACCTATCTCCCAACCA	20	59,9	124	NM_016239.3
MYO15A_66-R	ACCACACGACACAGTTCCAG	20	59,6	124	NM_016239.3
ESCO2_2-F	CCTCCCAGAAAATAGGGTTTT	21	58,5	201	NM_001017420
ESCO2_2-R	CACAGGCTGAGATTACCTG	20	59,4	201	NM_001017420

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
ESCO2_7-F	TGCAGCATGTACAGCATCAC	20	59,4	129	NM_001017420
ESCO2_7-R	GGTGGTAGAGGTGGTGGAAA	20	59,8	129	NM_001017420
ESCO2_11-F	TTGCTTCATGTTTGGCTGTT	20	59,3	107	NM_001017420
ESCO2_11-R	GGAAATTAGGGGTGTTGCAG	20	59,4	107	NM_001017420
ASXL3_2-F	TAAAAGCCCCTTCCCCTCTA	20	60,0	152	NM_030632.2
ASXL3_2-R	CTGCTTTGCTGTCATTGGTG	20	60,4	152	NM_030632.2
ASXL3_11-F	GAAAAGCCCAGCTTCTCCA	19	60,5	179	NM_030632.2
ASXL3_11-R	CATCCTGGCATTACAGATACT	22	59,1	179	NM_030632.2
CC2D1A_2-F	AGCCATGTGGTGAACCAAAG	20	61,0	189	NM_017721.4
CC2D1A_2-R	TCACCTTTGCCTTTGAGCTT	20	60,0	189	NM_017721.4
CC2D1A_14-F	ACTGCGAGCCAAGCAGAA	18	60,9	138	NM_017721.4
CC2D1A_14-R	CACAAGCCCAGAAGGTTTCAC	20	60,7	138	NM_017721.4
CC2D1A_16-F	GACTCACTGCCTTCTGTTTCC	21	58,9	118	NM_017721.4
CC2D1A_16-R	GGTGCAAGTGTCTGGCAC	18	58,7	118	NM_017721.4
CC2D1A_28-F	CTACCTGCTGAATGCCCATC	20	60,6	101	NM_017721.4
CC2D1A_28-R	CCACCCCATCTCCTAAGCT	19	59,1	101	NM_017721.4
COL6A1_12v2-F	CTCCCCACCCCAAATACC	18	60,0	148	NM_001848.2
COL6A1_12v2-R	AAGGCAGGAGTCAGATGCA	19	59,5	148	NM_001848.2
COL6A3_43-F	TGGATCACAGAAAGAATGTGAA	22	58,2	192	NM_004369.3
COL6A3_43-R	GGGTTGTATTTGAACGTCTTCC	22	59,7	192	NM_004369.3
CD96_2-F	CTCATGGCTCATGTTCTTTCTT	22	58,5	184	NM_198196.2
CD96_2-R	GGATGATAGACAGCAATCAGGT	22	58,1	184	NM_198196.2
CD96_15-F	GTGTGTGCATAAGACTCCCTCA	22	60,2	124	NM_198196.2
CD96_15-R	GGCTCTTGAATGCAAGTGTACT	22	58,5	124	NM_198196.2
COL6A2_6-F	TCAGAGGAGCTGTGGCAG	18	58,7	135	NM_001849.3
COL6A2_6-R	CCTGTCTTCCCTTCTGGC	18	58,3	135	NM_001849.3

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
SLC5A2_3-F	AGCCCTGCTCACTCCCTC	18	60,5	123	NM_003041.3
SLC5A2_3-R	CAGCAACAGCCAAGCCAC	18	61,6	123	NM_003041.3
SLC5A2_14-F	CCAGTGCCTGCTCTGGTT	18	60,0	116	NM_003041.3
SLC5A2_14-R	GGTCCTCGCTGATGTCCT	18	58,7	116	NM_003041.3
FBN2_2-F	CGCTTGTCATCACAGGC	18	61,4	118	NM_001999.3
FBN2_2-R	ATCCCTGCCAAGCACTCA	18	60,4	118	NM_001999.3
FBN2_23-F	GGAAGTAGGACCACACCTGCT	21	60,6	182	NM_001999.3
FBN2_23-R	CAGTCCCATCCAACGTAAGG	20	60,4	182	NM_001999.3
FBN2_65-F	CCCAAATCATTTCTGTCTTC	22	59,8	131	NM_001999.3
FBN2_65-R	GCCTTAGTTCCAGGATGTGCT	21	60,6	131	NM_001999.3
ADAMTS2_3-F	CCGTGTGCATGTGGTGTATC	20	60,9	108	NM_014244.4
ADAMTS2_3-R	GCTCTCCACACAGCCTGC	18	60,7	108	NM_014244.4
ADAMTS2_13-F	GATGCCACCTGTACTGCG	18	58,8	111	NM_014244.4
ADAMTS2_13-R	GCACACAGAGGCTGAAGG	18	58,0	111	NM_014244.4
ADAMTS2_22-F	CCAAGGCGACAAGTCAATATT	21	59,1	113	NM_014244.4
ADAMTS2_22-R	TGGTGAGGTTGTTGTACAGGTT	22	59,4	113	NM_014244.4
MMACHC_1-F	GCTCAGCGTGTAACGTGC	18	59,1	110	NM_015506.2
MMACHC_1-R	AAACTAACCTGGAAGGGGTAAA	22	58,1	110	NM_015506.2
MMACHC_2-F	CTCAAGCCCTTCTTGCAGA	19	59,3	147	NM_015506.2
MMACHC_2-R	GAGGAAGTGGAGGCAGCT	18	58,0	147	NM_015506.2
MMACHC_4-F	GGACCTCCATGACCTTGCT	19	60,1	113	NM_015506.2
MMACHC_4-R	CCTGGCAGCAGCACTACC	18	60,6	113	NM_015506.2
SLC5A1_2-F	AGGTATGTCCTTTTGGCTGG	20	59,1	120	NM_000343.3
SLC5A1_2-R	CTGCCAGGAAGAAGCCTC	18	58,6	120	NM_000343.3
SLC5A1_15-F	CCTATGACCTATTTTGTGGGCT	22	59,4	148	NM_000343.3
SLC5A1_15-R	GTCACCAGGATGATGCCA	18	58,9	148	NM_000343.3

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
COL6A2_26-F	GGCGTGGTGCAGTACAGC	18	61,7	153	NM_001849.3
COL6A2_26-R	GTAGGCAAACCTTGAGGGCTGA	21	61,5	153	NM_001849.3
BCKDHA_2-F	CTGGGTGCTGCTTCTGATG	19	60,6	178	NM_000709.3
BCKDHA_2-R	GGTAGATGGGGATTCCAGAGA	21	60,3	178	NM_000709.3
BCKDHA_3-F	AGGAGAAGGTGCTGAAGCTC	20	58,8	138	NM_000709.3
BCKDHA_3-R	ACAGGTAGGGGACCTCAGGT	20	59,8	138	NM_000709.3
BCKDHA_4-F	GCAGGATTTGGATGGCTC	18	59,1	100	NM_000709.3
BCKDHA_4-R	TTGGTCATGTAGAAGGAGATCC	22	58,1	100	NM_000709.3
BCKDHA_6-F	ATGCCAACAGGGTCGTCA	18	61,1	101	NM_000709.3
BCKDHA_6-R	GATGGGGCACTCAAGTGTG	19	60,1	101	NM_000709.3
COL6A1_14-F	AGGGCACCAAGTCTGACAG	19	58,8	211	NM_001848.2
COL6A1_14-R	ACAGAAGTCAAAACGGTCCAC	21	59,1	211	NM_001848.2
COL6A1_33-F	CATCCCAGGCTCAGACCA	18	60,8	131	NM_001848.2
COL6A1_33-R	TGACATTCTTCAGGAAGGCAT	21	59,7	131	NM_001848.2
SAG_2-F	GCACAGGATCTCGTGAGTAGG	21	59,9	136	NM_000541.4
SAG_2-R	CATGTTATCTGTCCCTGGCA	20	59,5	136	NM_000541.4
SAG_16-F	GAGTTTGCTCGCCATAATCTG	21	59,9	128	NM_000541.4
SAG_16-R	CGTTGCACTGGTAACTACAGGT	22	59,2	128	NM_000541.4
MYO15A_3-F	CTCTCACACAGATGCACTCCA	21	60,0	105	NM_016239.3
MYO15A_3-R	TGCCCACTCACTCCAGCT	18	60,6	105	NM_016239.3
ASXL3_3-F	AGAAGCTGTACCTCAGACTGCTT	23	58,9	141	NM_030632.2
ASXL3_3-R	CTGACTTTCCAGGGATTTTGA	21	59,2	141	NM_030632.2
ASXL3_8-F	ACCAAAGCTGAGGACATTGAC	21	59,2	149	NM_030632.2
ASXL3_8-R	TGCCTATCCACTTCTGGGAG	20	60,2	149	NM_030632.2
ASXL3_12-F	GAAGAGAGTCCCTGGTGCAG	20	60,0	161	NM_030632.2
ASXL3_12-R	GCAATGGAAGCCTGTTGATT	20	60,1	161	NM_030632.2

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
FANCC_14-F	ACCTCCTGGCAATGTCCAG	19	61,1	126	NM_000136.2
FANCC_14-R	AGTTGAGGAGAAGGTGCCTGA	21	61,3	126	NM_000136.2
ERCC3_2-F	AGAAATCCAGGAAGCGGC	18	60,3	129	NM_000122.1
ERCC3_2-R	CATCCACTTTGGTGCCTGA	19	60,7	129	NM_000122.1
ERCC3_8-F	CCAGTTCAAGATGTGGTCCAC	21	60,4	113	NM_000122.1
ERCC3_8-R	CCAGCATGGAGTAGGTGCTAA	21	60,3	113	NM_000122.1
ERCC3_14-F	AGAGCAACAGCAGCTCTTACAG	22	59,1	104	NM_000122.1
ERCC3_14-R	TACTCACCTGGCTGGATCTG	20	58,8	104	NM_000122.1
SLC5A1_7-F	TAGACAGGTCACCTCCACA	20	59,1	122	NM_000343.3
SLC5A1_7-R	GATTAAAGACCCCACCAGCA	20	59,9	122	NM_000343.3
SLC5A1_i14-F	AGGAGCTGTTTCAGACCAGTTCT	22	59,6	101	NM_000343.3
SLC5A1_i14-R	GTCTGGCTGGCATGATTCA	19	60,8	101	NM_000343.3
GPR15_1-F	TTCCTGACTGGAGTGCTGG	19	60	169	NM_005290.3
GPR15_1-R	TCCACAGTCCTAGAGATGCTTC	22	58,6	169	NM_005290.3
VCP_2-F	AGGTGATGACCTATCAACAGCC	22	60,4	112	NM_007126.3
VCP_2-R	GCTTACCTGGGACAAGGACAC	21	60,9	112	NM_007126.3
VCP_8-F	GCTGGTGAGTCTGAGAGCAA	20	59,3	134	NM_007126.3
VCP_8-R	TATCCCCTCAGGTAAGCTCCT	21	59,2	134	NM_007126.3
VCP_16-F	GGAGGTAGAAGAGGATGATCCA	22	59,5	137	NM_007126.3
VCP_16-R	GACTCTGCTGAAGGGTCTGG	20	60	137	NM_007126.3
DNMT3B_3-F	ACTCTCCAAGAGGGAGGTGTC	21	59,7	103	NM_006892.3
DNMT3B_3-R	CGTGATGAAAGCCAAAGACA	20	59,8	103	NM_006892.3
DNMT3B_11-F	ACGACTCAGCCACCTCTGAC	20	60,5	103	NM_006892.3
DNMT3B_11-R	TCACCTCGGCTCTGATCTTC	20	60,5	103	NM_006892.3
DNMT3B_22-F	ACAGACAATAACCACCAAGTCG	22	59	118	NM_006892.3
DNMT3B_22-R	CCTTGCTCACCTTTCGAGC	19	61,1	118	NM_006892.3

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
SBF1_2-F	GATCCTCAAGCCTCCTGGT	19	59,2	123	NM_002972.3
SBF1_2-R	CCTCCCAGTCCTTCTCTGG	19	59,8	123	NM_002972.3
SBF1_12-F	CGTGGGCTGGTAGAGGAC	18	59,2	115	NM_002972.3
SBF1_12-R	GCACCTCATCGAACAGGTC	19	59,2	115	NM_002972.3
SBF1_26-F	ATGACCATGAGCAGCCTG	18	58,2	105	NM_002972.3
SBF1_26-R	GAAGGGCTCAGACTTGGC	18	58,5	105	NM_002972.3
SBF1_35-F	GTGCAGGGCTGCTGTATG	18	58,9	145	NM_002972.3
SBF1_35-R	CAGCTTACCTCTGCGTCCT	19	58,2	145	NM_002972.3
SBF1_40-F	TGTGGACACAGAGTGCAAGG	20	60,9	123	NM_002972.3
SBF1_40-R	CCAAGGCTCACGTCAAAGA	19	60	123	NM_002972.3
ITPR1_4-F	GGAAAAGCCCTGGGATATCT	20	59,4	127	NM_002222.5
ITPR1_4-R	CGGTTTCTGGCTGTACAACAC	21	60,6	127	NM_002222.5
ITPR1_6-F	GAAAACAGGAAATTGCTGGG	20	59,5	137	NM_002222.5
ITPR1_6-R	TCCAAACCCTGTCTTAGGTGTT	22	59,9	137	NM_002222.5
ITPR1_10-F	AGGAAGAAGCAGCACGTCTT	20	59,2	100	NM_002222.5
ITPR1_10-R	ACCCTACCCTTACCTCCACCT	21	60,1	100	NM_002222.5
ITPR1_20-F	GCTGGATGTCGATCTCATTCT	21	59,3	123	NM_002222.5
ITPR1_20-R	GTGACTTGTTTCCTGGGGATC	20	59,4	123	NM_002222.5
ITPR1_38-F	CCTGAGGGGAAATGATGACCA	20	60,9	118	NM_002222.5
ITPR1_38-R	AGGTGGGTTTTGAAAGGTCC	20	60,2	118	NM_002222.5
ITPR1_40-F	AGCTCTATGAGCAGGGGTGA	20	60	123	NM_002222.5
ITPR1_40-R	TTCATGGAACACTCGGTCAC	20	59,5	123	NM_002222.5
ITPR1_44-F	ACTGCATAGCCACCCATGA	19	60,1	113	NM_002222.5
ITPR1_44-R	TGCCTTCAGTTCTAACACAAGG	22	59,4	113	NM_002222.5
ITPR1_48-F	GAACAGATAGTCTTTCCCGTGC	22	60,1	136	NM_002222.5
ITPR1_48-R	AGAGGTCTTCAGACCGCAGA	20	60,1	136	NM_002222.5

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
ITPR1_52-F	TGGACGGTCCATCATCCT	18	59,8	119	NM_002222.5
ITPR1_52-R	CATTGGGCAGCCTATCTACTTC	22	60,1	119	NM_002222.5
ITPR1_57-F	CCAGGATGAGAGCCATGTC	19	59,1	141	NM_002222.5
ITPR1_57-R	CCTGATCCTTTAATTCCGACAG	22	60	141	NM_002222.5
SMARCA4_3-F	TTCCACATGCTGACCCTG	18	59,1	112	NM_001128849.1
SMARCA4_3-R	ATCCCCATTCCTTTCATCTG	20	58,8	112	NM_001128849.1
SMARCA4_16-F	ATCAAAGGTTTGGAGTGGCT	20	58,6	159	NM_001128849.1
SMARCA4_16-R	AGGCACGATGATGAGGAAG	19	58,8	159	NM_001128849.1
SMARCA4_30-F	CATGACACAGCCAGCAGTG	19	60	131	NM_001128849.1
SMARCA4_30-R	CACGTCCCCAGTGTTGTG	18	59,5	131	NM_001128849.1
SMARCA4_34-F	GAAGACTCCATCGTCTTGCGAG	21	60	112	NM_001128849.1
SMARCA4_34-R	CTTCCTCCTCGCCCTCTT	18	59,5	112	NM_001128849.1
SLC5A2_1-F	AGAATGGAGGAGCACACAGAG	21	59,5	105	NM_003041.3
SLC5A2_1-R	CAGGAAATATGCAGCAATGAC	21	58,3	105	NM_003041.3
SLC5A2_4-F	GGTCATCACGATGCCACA	18	60,1	114	NM_003041.3
SLC5A2_4-R	GCACTCACTGAGATCTTGGTGA	22	60,5	114	NM_003041.3
MARVELD2_2-F	ACCAGTGAATGCAGTGTTCTG	21	58,8	137	NM_001038603.2
MARVELD2_2-R	GTCTCCGAGCTGCCTCAT	18	59	137	NM_001038603.2
MARVELD2_5-F	CGCTATAAAGCTGTGTTCCAAG	22	59,1	105	NM_001038603.2
MARVELD2_5-R	GCTCATCACTGCATCCAGC	19	60,5	105	NM_001038603.2
NAA10_2-F	CCAGAGGACCTAATGAACATGC	22	60,9	115	NM_003491.3
NAA10_2-R	TTCAGAAGCTGCCCACCT	18	59,5	115	NM_003491.3
NAA10_8-F	GAGCTGAAAGAGAAGGGCAG	20	59,3	132	NM_003491.3
NAA10_8-R	ACCACTATCCTCGGCAGC	18	58,8	132	NM_003491.3
CC2D1A_26-F	CCAGCAGTACCAGGACATCA	20	59,7	109	NM_017721.4
CC2D1A_26-R	CCACCAGATGCCCATCTC	18	60	109	NM_017721.4

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
SBF1_3-F	ACTGCTGAGCCTTCCCTG	18	59,1	141	NM_002972.3
SBF1_3-R	CTCCCAGAAGGTCAAGCAG	19	58,5	141	NM_002972.3
SBF1_24-F	ACGAGGAGGTGGGGTCTG	18	61,1	118	NM_002972.3
SBF1_24-R	CCAGGTGTGTGGGCAGAG	18	61,4	118	NM_002972.3
GYG1_2-F	CATCTCTGAAACAGCACAGGA	21	59	132	NM_004130.3
GYG1_2-R	GCAACAGGGAGAAGGATGTC	20	59,7	132	NM_004130.3
GYG1_8-F	GGAAGGAACGATGGGAACA	19	60,9	136	NM_004130.3
GYG1_8-R	CAAGGCTTGTGAAGTGGATGT	21	60,2	136	NM_004130.3
BTK_1-F	AGCAGGGAACCAGATAGCAT	20	58,8	121	NM_000061.2
BTK_1-R	AGAGGAAGGACAGTCTGAGCA	21	59,2	121	NM_000061.2
BTK_3-F	CATCTGGTTGCTTAATCCCTCT	22	59,6	158	NM_000061.2
BTK_3-R	GGAATCTGTCTTTCTGGAGGAG	22	59,3	158	NM_000061.2
BTK_4-F	GGTGAAGAGTCCAGTGAAATGG	22	60,9	160	NM_000061.2
BTK_4-R	CTGGGTCCTCGTAGCCTTC	19	59,8	160	NM_000061.2
BTK_5-F	CTGAACACCATTGCTGACTGA	21	59,9	194	NM_000061.2
BTK_5-R	GTTCTTCAGTTGGGGAGAAGAC	22	59,2	194	NM_000061.2
BTK_6-F	TGCTTGAAGTTCACCACTAAGC	22	59,6	149	NM_000061.2
BTK_6-R	GATCCAGAAGCAAGGGTGA	19	58,7	149	NM_000061.2
BTK_8-F	ACCAGTCTCCACAAGTGAGCT	21	59	124	NM_000061.2
BTK_8-R	TGGTAAGTTGCTTTCCTCCAAG	22	60,6	124	NM_000061.2
BTK_10-F	CATGGACAAGCCCTGGAG	18	60,2	126	NM_000061.2
BTK_10-R	AGCAGTTGCTCAGCCTGAC	19	59,3	126	NM_000061.2
BTK_11-F	CCACTTCCTCCTACAGACAGC	21	59	127	NM_000061.2
BTK_11-R	CACTCACCTGTGGATTTAGC	21	59,6	127	NM_000061.2
BTK_12-F	GTTGACCTTTGTGCCCAAG	19	59,1	103	NM_000061.2
BTK_12-R	TACTGGCTCTGAGGTGTGGA	20	59,4	103	NM_000061.2

(cont.) Table S2 – qPCR primers sequence, base pairs, melting temperatures, amplicon base pairs and RefSeq used during design.

Primer name	Primer sequence (5'-3')	Primer bp	Primer Tm	Amplicon bp	RefSeq
BTK_14-F	GATCATGGGAAATTGATCCAA	21	59,6	145	NM_000061.2
BTK_14-R	TCATCTTCAGACATGGAGCCT	21	59,8	145	NM_000061.2
BTK_15-F	TGAGAAGCTGGTGCAGTTGT	20	59,6	149	NM_000061.2
BTK_15-R	CCTTGCACATCTCTAGCAGC	20	58,8	149	NM_000061.2
BTK_16-F	GTTTGCACACTACAGGCAGCTC	20	58,7	143	NM_000061.2
BTK_16-R	CCTACCCATGTTTCATACTGTGC	23	60,7	143	NM_000061.2
BTK_17-F	ATGTCCTGGATGATGAATACACA	23	59,2	101	NM_000061.2
BTK_17-R	AGATTTGCTGCTGAACCTTGCT	21	59,3	101	NM_000061.2
BTK_19-F	ATGTCATGGATGAAGAATCCTG	22	58,9	116	NM_000061.2
BTK_19-R	GCTCCAGGGCTCCTAAGC	18	60,1	116	NM_000061.2
MCCC2_1-F	CCTCTACCAGGTAGGCTGAGC	21	60,4	102	NM_022132.4
MCCC2_1-R	GACAAGAGAGCAGCAGTTGTTG	22	60,2	102	NM_022132.4
MCCC2_10-F	TGCAGGTCACCATTTGAACC	19	60,5	137	NM_022132.4
MCCC2_10-R	GCTGGTCATAAAGCTCACAGTTC	23	60,3	137	NM_022132.4
MCCC2_17-F	TTCCTTGGCATTCTCTGCAC	19	59,8	141	NM_022132.4
MCCC2_17-R	ACTGAGACCCAAGACCAGTCTG	22	60,7	141	NM_022132.4
ABCA3_5-F	GCTTGAAGATTCAGTCGGAAA	21	59,4	133	NM_001089.2
ABCA3_5-R	CTGTGAGAAGGGATGTAGGCA	21	60,3	133	NM_001089.2
ABCA3_12-F	CATCCAGTGGCGAGACCT	18	59,8	121	NM_001089.2
ABCA3_12-R	CTCCATGTACCAGGTCACCAG	21	60,4	121	NM_001089.2
ABCA3_22-F	TCTTCAGGGCTTCTGTGGAG	20	60,5	131	NM_001089.2
ABCA3_22-R	AGTGGCTGGAGAGTGGTACG	20	60,3	131	NM_001089.2
ABCA3_32-F	GAGGACTCCAGTGCTGAGC	19	58,6	116	NM_001089.2
ABCA3_32-R	CATGCCTTGGTGCTCATCT	19	59,8	116	NM_001089.2

ANNEX III - Method Validation – Results Comparison

Table S3- Results comparison between qPCR and previous results for methodology validation

Sample	Gene	Fragment	MLPA Result	aCGH Result	Other Tests	qPCR Result	Prediction Value		
							MLPA	aCGH	Other
A1	MECP2	MECP2_2	Normal	-	-	Normal	0	-	-
A1	MECP2	MECP2_3	Normal	-	-	Normal	0	-	-
A1	MECP2	MECP2_4A	Normal	-	-	Normal	0	-	-
A1	MECP2	MECP2_4C	Normal	-	-	Normal	0	-	-
A4	MECP2	MECP2_2	Normal	Normal	-	Normal	0	0	-
A4	MECP2	MECP2_3	c.27-? _704+?del; Heterozygous deletion of exon 3 and part of exon 4	arr Xq28(153,297,503- 153,314,668)x1; Heterozygous deletion of exon 3	-	Heterozygous Deletion	0	0	-
A4	MECP2	MECP2_4A	c.27-? _704+?del; Heterozygous deletion of exon 3 and part of exon 4	Normal	-	Heterozygous Deletion	0	1	-
A4	MECP2	MECP2_4C	Normal	Normal	-	Normal	0	0	-
A5	MECP2	MECP2_2	c.1-? _c.1461+?dup; Heterozygous duplication	-	-	Heterozygous Duplication	0	-	-

(cont.) Table S3- Results comparison between qPCR and previous results for methodology validation.

Sample	Gene	Fragment	MLPA Result	aCGH Result	Other Tests	qPCR Result	Prediction Value		
							MLPA	aCGH	Other
A5	MECP2	MECP2_3	c.1- ?_c.1461+?dup; Heterozygous duplication	-	-	Heterozygous Duplication	0	-	-
A5	MECP2	MECP2_4A	c.1- ?_c.1461+?dup; Heterozygous duplication	-	-	Heterozygous Duplication	0	-	-
A5	MECP2	MECP2_4C	c.1- ?_c.1461+?dup; Heterozygous duplication	-	-	Heterozygous Duplication	0	-	-
A10	NF1	NF1_13	Hemizygous deletion in <i>DMD</i> gene	-	-	Normal	0	-	-
A10	NF1	NF1_14	Hemizygous deletion in <i>DMD</i> gene	-	-	Normal	0	-	-
A10	NF1	NF1_58	Hemizygous deletion in <i>DMD</i> gene	-	-	Normal	0	-	-
A11	NF1	NF1_13	c.1- ?_8457+?del; Heterozygous deletion	-	-	Heterozygous Deletion	0	-	-

(cont.) Table S3- Results comparison between qPCR and previous results for methodology validation.

Sample	Gene	Fragment	MLPA Result	aCGH Result	Other Tests	qPCR Result	Prediction Value		
							MLPA	aCGH	Other
A11	NF1	NF1_14	c.1-? _8457+?del; Heterozygous deletion	-	-	Heterozygous Deletion	0	-	-
A11	NF1	NF1_58	c.1-? _8457+?del; Heterozygous deletion	-	-	Heterozygous Deletion	0	-	-
A12	NF1	NF1_13	Normal	-	Duplication of exon 13 detected by NGS and qPCR at another lab	Normal	0	-	-1
A12	NF1	NF1_14	Normal	-	Normal	Normal	0	-	0
A12	NF1	NF1_58	Normal	-	Normal	Normal	0	-	0
A10	PARK2	PARK2_4	Hemizygous deletion in <i>DMD</i> gene	-	-	Normal	0	-	-
A10	PARK2	PARK2_7	Hemizygous deletion in <i>DMD</i> gene	-	-	Normal	0	-	-
A10	PARK2	PARK2_12	Hemizygous deletion in <i>DMD</i> gene	-	-	Normal	0	-	-

(cont.) Table S3- Results comparison between qPCR and previous results for methodology validation.

Sample	Gene	Fragment	MLPA Result	aCGH Result	Other Tests	qPCR Result	Prediction Value		
							MLPA	aCGH	Other
A13	PARK2	PARK2_4	c.172-?_534+?del; c.172-?_734+?del; Compound heterozygous deletion of exons 3 to 4 and 3 to 6	-	Sequencing failure of exons 3 and 4 (Sanger)	Homozygous/Compound Heterozygous Deletion	0	-	0
A13	PARK2	PARK2_7	Normal	-	Normal	Normal	0	-	0
A13	PARK2	PARK2_12	Normal	-	Normal	Normal	0	-	0
A14	PARK2	PARK2_4	c.413-?_871+?del; Heterozygous deletion of exons 4 to 7	-	-	Heterozygous Deletion	0	-	-
A14	PARK2	PARK2_7	c.413-?_871+?del; Heterozygous deletion of exons 4 to 7	-	-	Heterozygous Deletion	0	-	-
A14	PARK2	PARK2_12	Normal	-	-	Normal	0	-	-

ANNEX IV – Primers Validation

Table S4 - Primers efficiency, R^2 and PCR characteristics for the tested genes.

Primer	Efficiency	R^2	Primer Volume (μ L)	Melting Temperature ($^{\circ}$ C)
ABCA3_5	0,85	0,996	0,4	99
ABCA3_12	0,95	0,996	0,4	99
ABCA3_22	0,92	0,993	0,4	99
ABCA3_32	0,83	0,992	0,4	99
ADAMTS2_3	1,10	0,988	0,4	95
ADAMTS2_13	1,12	0,997	0,4	95
ADAMTS2_22	1,01	0,996	0,4	95
ASXL3_2	0,87	0,957	0,4	95
ASXL3_3	0,82	0,994	0,9	95
ASXL3_8	0,89	0,990	0,4	95
ASXL3_11	0,84	0,983	0,4	95
ASXL3_12	0,85	0,997	0,4	95
BCKDHA_2	0,91	0,995	0,9	95
BCKDHA_3	0,93	0,987	0,4	95
BCKDHA_4	0,86	0,992	0,4	95
BCKDHA_6	0,90	0,994	0,4	95
BTK_1	0,94	0,974	0,4	95
BTK_3	0,86	0,993	0,4	95
BTK_4	0,79	0,978	1,0	95
BTK_5	0,87	0,991	1,0	95
BTK_6	0,81	0,981	1,0	95
BTK_8	0,81	0,977	0,6	95
BTK_10	0,89	0,991	0,4	95
BTK_11	0,83	0,979	0,8	95
BTK_12	0,82	0,983	0,8	95
BTK_14	0,82	0,983	0,4	95
BTK_15	0,92	0,993	1,0	95
BTK_16	0,80	0,991	0,4	95
BTK_17	0,89	0,988	0,8	95
BTK_19	0,96	0,996	0,8	95
CC2D1A_2	0,91	0,994	0,4	95
CC2D1A_14	0,85	0,987	0,4	95
CC2D1A_16	1,00	0,978	0,4	95
CC2D1A_28	1,01	0,992	0,4	99
CD96_2	0,91	0,996	0,4	95
CD96_15	0,87	0,995	0,4	95
COL6A1_8	1,04	0,996	0,4	99
COL6A1_9	0,93	0,995	0,3	99
COL6A1_14	1,00	0,989	0,4	99
COL6A1_33	0,90	0,992	0,4	99
COL6A2_i1	0,96	0,981	0,4	95

(cont.) Table S4 - Primers efficiency, R² and PCR characteristics for the tested genes.

Primer	Efficiency	R ²	Primer Volume (μL)	Melting Temperature (°C)
COL6A2_5	0,83	0,981	0,4	95
COL6A2_10	0,80	0,990	0,4	95
COL6A2_11	0,87	0,991	0,4	95
COL6A2_26	1,06	0,957	0,4	95
DNMT3B_3	1,00	0,996	0,6	95
DNMT3B_11	1,01	0,997	0,6	95
DNMT3B_22	0,81	0,992	0,4	95
ERCC3_2	1,02	0,991	0,4	95
ERCC3_8	0,88	0,990	0,4	95
ERCC3_14	0,85	0,992	0,4	95
ESCO2_2	0,86	0,968	0,4	95
ESCO2_7	0,85	0,983	0,4	95
ESCO2_11	0,88	0,938	0,4	95
FANCC_1	1,10	0,972	0,4	99
FANCC_2	0,83	0,973	0,4	95
FANCC_4	0,85	0,986	0,8	95
FANCC_14	0,86	0,991	0,8	95
FBN2_2	0,98	0,989	0,4	95
FBN2_23	0,97	0,998	0,4	95
FBN2_65	0,88	0,995	0,4	95
GYG1_2	1,04	0,992	0,6	99
GYG1_8	0,88	0,992	0,4	99
IL7R_3	0,87	0,973	0,4	95
IL7R_8	0,90	0,974	0,4	95
ITPR1_4	1,03	0,994	0,4	95
ITPR1_6	0,98	0,993	0,4	95
ITPR1_10	0,86	0,989	0,4	95
ITPR1_20	0,98	0,994	0,4	95
ITPR1_38	0,97	0,992	0,4	95
ITPR1_40	0,94	0,985	0,4	95
ITPR1_44	0,94	0,984	0,4	95
ITPR1_48	0,82	0,992	0,6	95
ITPR1_52	0,90	0,981	0,4	95
ITPR1_57	0,96	0,992	0,4	95
MARVELD2_2	1,02	0,997	0,4	95
MARVELD2_5	0,95	0,997	0,4	95
MCCC2_1	0,95	0,993	0,4	99
MCCC2_10	0,88	0,993	0,4	95
MCCC2_17	0,87	0,990	0,4	95
MGME1_2	0,83	0,947	0,4	95
MGME1_3	0,95	0,996	0,6	95
MGME1_5	0,83	0,979	0,4	95

(cont.) Table S4 - Primers efficiency, R² and PCR characteristics for the tested genes.

Primer	Efficiency	R ²	Primer Volume (μL)	Melting Temperature (°C)
MMACHC_1	0,94	0,990	0,6	95
MMACHC_2	1,01	0,993	0,4	95
MMACHC_4	0,86	0,996	0,4	95
MVK_3	0,93	0,980	0,4	95
MVK_4	0,73	0,965	0,9	95
MVK_6	0,98	0,972	0,4	95
MYO15A_3	1,16	0,989	0,4	95
MYO15A_16	0,93	0,991	0,4	95
MYO15A_30	0,91	0,991	0,4	95
MYO15A_45	0,89	0,985	0,4	95
MYO15A_66	0,89	0,995	0,4	95
NAA10_2	1,04	0,983	0,4	95
NAA10_8	1,05	0,989	0,4	95
PEX1_6	0,90	0,988	0,6	95
PEX1_9	0,90	0,990	0,4	95
PEX1_12	1,01	0,994	0,4	95
PEX1_14	0,91	0,986	0,4	95
PEX1_24	0,99	0,996	0,4	95
SAG_2	0,86	0,993	0,4	95
SAG_16	1,00	0,989	0,4	95
SBF1_3	1,06	0,993	0,4	95
SBF1_12	1,02	0,992	0,4	95
SBF1_26	0,98	0,985	0,2	99
SBF1_35	1,11	0,987	0,45	95
SBF1_40	0,88	0,983	0,4	95
SLC5A1_2	0,93	0,992	0,4	95
SLC5A1_7	0,93	0,995	0,4	95
SLC5A1_i14	0,82	0,997	0,4	95
SLC5A1_15	0,92	0,964	0,4	95
SLC5A2_1	1,00	0,992	0,6	95
SLC5A2_4	0,86	0,994	0,6	99
SLC5A2_14	0,90	0,995	0,4	95
SMARCA4_3	0,93	0,969	0,4	95
SMARCA4_16	0,97	0,994	0,4	95
SMARCA4_30	0,93	0,990	0,4	95
SMARCA4_34	0,84	0,995	0,6	99
THPO_3	0,98	0,983	0,6	95
THPO_4	0,80	0,978	0,4	95
THPO_6	0,80	0,949	0,4	95
VCP_2	1,00	1,000	0,6	95
VCP_8	0,80	0,992	0,4	95
VCP_16	0,82	0,992	0,4	95

ANNEX V – Relative Quantitation Results

Table S5 - Relative quantitation results for the samples used as normal controls.

Control Samples			Control Samples		
Primer	Sample	Copy Number	Primer	Sample	Copy Number
ABCA3_5	POOL	1,01	COL6A1_33	POOL	1,02
ABCA3_12	POOL	1,02	COL6A1_8	POOL	1,02
ABCA3_22	POOL	0,97	COL6A1_9	POOL	1,14
ABCA3_32	POOL	1,01	COL6A2_10	A8	1,00
ADAMTS2_13	POOL	0,93	COL6A2_11	A17	0,89
ADAMTS2_22	POOL	1,10	COL6A2_26	POOL	0,90
ADAMTS2_3	POOL	1,09	COL6A2_5	A8	1,12
ASXL3_11	POOL	0,99	COL6A2_i1	A17	1,09
ASXL3_12	POOL	0,88	COL6A3_1	POOL	1,01
ASXL3_2	POOL	0,90	COL6A3_16	POOL	1,05
ASXL3_3	POOL	0,93	COL6A3_43	POOL	0,92
ASXL3_8	POOL	1,00	DNMT3B_11	POOL	0,97
BCKDHA_2	POOL	0,97	DNMT3B_22	POOL	0,96
BCKDHA_3	POOL	0,95	DNMT3B_3	POOL	0,99
BCKDHA_4	POOL	0,99	ERCC3_14	POOL	1,01
BCKDHA_6	POOL	1,04	ERCC3_2	POOL	0,99
BTK_1	POOL	1,02	ERCC3_8	POOL	0,99
BTK_10	POOL	0,99	ESCO2_11	POOL	1,01
BTK_11	POOL	0,99	ESCO2_2	POOL	0,99
BTK_12	POOL	0,91	ESCO2_7	POOL	1,04
BTK_14	POOL	1,05	FANCC_1	POOL	1,10
BTK_15	POOL	1,02	FANCC_14	POOL	1,07
BTK_16	POOL	0,96	FANCC_2	POOL	1,02
BTK_17	POOL	1,06	FANCC_4	POOL	0,97
BTK_19	POOL	1,02	FBN2_2	POOL	1,08
BTK_3	POOL	1,06	FBN2_23	POOL	1,09
BTK_4	POOL	1,07	FBN2_65	POOL	0,98
BTK_5	POOL	0,99	GYG1_2	POOL	1,05
BTK_6	POOL	1,06	GYG1_8	POOL	1,07
BTK_8	POOL	1,01	IL7R_3	POOL	1,07
CC2D1A_14	POOL	0,98	IL7R_3	POOL	0,96
CC2D1A_16	POOL	1,02	IL7R_8	POOL	1,10
CC2D1A_2	POOL	0,96	IL7R_8	POOL	1,05
CC2D1A_28	POOL	1,03	ITPR1_10	POOL	1,09
CD96_15	POOL	1,03	ITPR1_20	POOL	0,96
CD96_2	POOL	0,95	ITPR1_38	POOL	0,92
COL6A1_14	POOL	1,07	ITPR1_4	POOL	0,95
COL6A1_14	POOL	0,98	ITPR1_40	POOL	1,00

(cont.) Table S5 - Relative quantitation results for the samples used as normal controls.

Control Samples			Control Samples		
Primer	Sample	Copy Number	Primer	Sample	Copy Number
ITPR1_44	POOL	1,06	PEX1_6	POOL	0,98
ITPR1_48	POOL	0,97	PEX1_9	POOL	1,03
ITPR1_52	POOL	1,13	SAG_16	POOL	1,01
ITPR1_57	POOL	1,07	SAG_2	POOL	0,99
ITPR1_6	POOL	0,92	SBF1_12	POOL	1,00
MARVELD2_2	POOL	0,98	SBF1_26	POOL	1,03
MARVELD2_5	POOL	1,05	SBF1_3	POOL	1,06
MCCC2_10	POOL	0,98	SBF1_35	POOL	1,11
MCCC2_17	POOL	0,99	SBF1_40	POOL	1,01
MCCC2_2	POOL	1,07	SLC5A1_15	POOL	1,06
MGME1_2	POOL	1,08	SLC5A1_2	POOL	1,05
MGME1_3	POOL	1,13	SLC5A1_7	POOL	1,03
MGME1_5	POOL	1,09	SLC5A1_i14	POOL	1,03
MMACHC_1	POOL	1,09	SLC5A2_1	POOL	1,01
MMACHC_2	POOL	1,07	SLC5A2_14	POOL	0,99
MMACHC_4	POOL	1,07	SLC5A2_4	POOL	1,08
MVK_3	POOL	0,95	SMARCA4_16	POOL	1,11
MVK_4	POOL	1,00	SMARCA4_3	POOL	1,05
MVK_6	POOL	1,07	SMARCA4_30	POOL	0,99
MYO15A_16	POOL	0,96	SMARCA4_34	POOL	1,02
MYO15A_3	POOL	1,00	THPO_3	POOL	1,02
MYO15A_30	POOL	1,11	THPO_3	CT_aCGH	1,08
MYO15A_45	POOL	0,94	THPO_4	POOL	1,07
MYO15A_66	POOL	0,95	THPO_4	CT_aCGH	1,02
NAA10_2	POOL	1,00	THPO_6	POOL	1,00
NAA10_8	POOL	1,02	THPO_6	CT_aCGH	1,15
PEX1_12	POOL	1,05	VCP_16	POOL	0,91
PEX1_14	POOL	1,00	VCP_2	POOL	0,98
PEX1_24	POOL	1,05	VCP_8	POOL	0,95

Table S6 - Relative quantitation results for the test samples scored as normal.

Normal Samples			Normal Samples		
Primer	Sample	Copy Number	Primer	Sample	Copy Number
ABCA3_5	A80	1,01	COL6A1_9	A20	1,01
ABCA3_12	A80	0,93	COL6A2_i1	A17	0,81
ABCA3_22	A80	1,00	COL6A2_10	A20	0,96
ADAMTS2_13	A56	0,95	COL6A2_11	A20	1,11
ADAMTS2_22	A56	0,91	COL6A2_26	A20	0,87
ADAMTS2_3	A56	1,08	COL6A2_5	A20	0,89
ASXL3_11	A49	1,09	COL6A3_1	A20	0,91
ASXL3_11	A48	0,99	COL6A3_16	A20	1,09
ASXL3_12	A49	1,03	COL6A3_43	A20	1,04
ASXL3_12	A48	0,94	DNMT3B_11	A65	1,06
ASXL3_2	A49	1,19	DNMT3B_22	A65	0,99
ASXL3_2	A48	0,99	DNMT3B_3	A65	0,97
ASXL3_3	A49	1,15	ERCC3_14	A58	0,92
ASXL3_3	A48	1,03	ERCC3_2	A58	0,90
ASXL3_8	A49	1,10	ERCC3_8	A58	0,96
ASXL3_8	A48	1,12	ESCO2_11	A34	0,93
BCKDHA_4	A53	0,85	ESCO2_2	A34	1,12
BCKDHA_6	A53	0,85	ESCO2_7	A34	0,97
BTK_1	A68	0,98	FANCC_1	A16	0,91
BTK_10	A68	0,93	FANCC_14	A16	0,94
BTK_11	A68	0,93	FANCC_2	A16	1,12
BTK_12	A68	0,99	FANCC_4	A16	1,14
BTK_14	A68	1,04	FBN2_2	A59	0,93
BTK_15	A68	0,94	FBN2_23	A59	1,06
BTK_16	A68	0,95	FBN2_65	A59	0,97
BTK_17	A68	1,06	GYG1_2	A76	0,98
BTK_19	A68	1,06	GYG1_8	A76	0,90
BTK_3	A68	0,99	IL7R_3	A66	1,11
BTK_4	A68	0,88	IL7R_3	A32	0,97
BTK_5	A68	0,92	IL7R_8	A66	1,07
BTK_6	A68	0,96	IL7R_8	A32	0,90
BTK_8	A68	0,97	ITPR1_10	A64	0,97
CC2D1A_14	A57	1,05	ITPR1_20	A64	0,93
CC2D1A_16	A57	1,15	ITPR1_38	A64	0,99
CC2D1A_2	A57	1,09	ITPR1_4	A64	1,06
CC2D1A_28	A57	1,08	ITPR1_40	A64	0,93
CD96_15	A62	0,98	ITPR1_44	A64	1,00
CD96_2	A62	1,09	ITPR1_48	A64	0,90
COL6A1_33	A20	0,85	ITPR1_52	A64	0,90
COL6A1_8	A20	0,97	ITPR1_57	A64	0,88

(cont.) Table S6 - Relative quantitation results for the test samples scored as normal.

Normal Samples			Normal Samples		
Primer	Sample	Copy Number	Primer	Sample	Copy Number
ITPR1_6	A64	0,93	SAG_16	A55	1,09
MARVELD2_2	A75	1,13	SAG_2	A55	1,00
MARVELD2_5	A75	1,16	SBF1_12	A63	0,94
MCCC2_10	A79	0,98	SBF1_26	A63	0,97
MCCC2_17	A79	0,90	SBF1_3	A63	1,10
MCCC2_2	A79	0,96	SBF1_35	A63	0,95
MGME1_2	A33	0,88	SBF1_40	A63	0,93
MGME1_3	A33	0,94	SLC5A1_15	A52	0,85
MGME1_5	A33	1,11	SLC5A1_2	A52	0,91
MMACHC_1	A54	0,93	SLC5A1_7	A52	1,14
MMACHC_2	A54	0,88	SLC5A1_i14	A52	0,98
MMACHC_4	A54	1,02	SLC5A2_1	A60	1,06
MVK_3	A50	1,07	SLC5A2_14	A60	0,93
MVK_4	A50	1,14	SLC5A2_4	A60	0,91
MVK_6	A50	0,91	SMARCA4_16	A77	0,93
MYO15A_16	A35	1,04	SMARCA4_3	A77	1,13
MYO15A_3	A35	1,08	SMARCA4_30	A77	0,94
MYO15A_30	A35	1,08	SMARCA4_34	A77	1,07
MYO15A_45	A35	1,08	THPO_3	A67	1,02
MYO15A_66	A35	1,08	THPO_3	A25	0,92
NAA10_2	A78	1,17	THPO_4	A67	0,89
NAA10_8	A78	0,99	THPO_4	A25	0,91
PEX1_12	A50	0,89	THPO_6	A67	0,93
PEX1_14	A50	0,95	THPO_6	A25	0,97
PEX1_24	A50	0,89	VCP_16	A61	0,92
PEX1_6	A50	0,93	VCP_2	A61	0,92
PEX1_9	A50	0,92	VCP_8	A61	0,91

Table S7 - Relative quantitation results for the test samples scored as deleted and duplicated.

Deleted Samples			Duplicated Samples		
Primer	Sample	Copy Number	Primer	Sample	Copy Number
COL6A1_14	A20	0,63	BTK_1	POOL_F	2,13
COL6A1_14	A20	0,52	BTK_3	POOL_F	2,01
ABCA3_32	A80	0,47	BTK_5	POOL_F	1,99
ABCA3_32	A80	0,50	BTK_6	POOL_F	2,06
BCKDHA_2	A53	0,01	BTK_8	POOL_F	1,96
BCKDHA_3	A53	0,03	BTK_10	POOL_F	2,12
			BTK_11	POOL_F	2,36
			BTK_12	POOL_F	2,23
			BTK_14	POOL_F	2,17
			BTK_15	POOL_F	1,96
			BTK_16	POOL_F	2,02
			BTK_17	POOL_F	2,01
			BTK_19	POOL_F	1,58
			NAA10_2	POOL_F	1,28
			NAA10_8	POOL_F	1,43